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Estimating Total, Merchantable, and Defect Volumes of Individual Trees for Four Regions of Alberta

by

Valerie M. LeMay

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Estimating Total, Merchantable, and Defect Volumes of Individual Trees for Four Regions of Alberta submitted by Valerie M. LeMay in partial fulfilment of the requirements for the degree of Master of Science.

Abstract

Results are presented for the analysis of methods for predicting total, merchantable, and defect volumes of individual trees. The methodology implemented in comparing methods included regression analysis, analysis of variance, and multiple comparison analysis.

The study area was confined to four regions of Alberta representing a variety of forested ecosystems. For each of the three types of tree volume, prediction methods were chosen for testing based on prior accuracy and popularity. The methods presently in use by the Alberta Forest Service were included in the study.

For total volume, standard and local volume functions were compared. The standard volume functions were significantly more accurate. Species or regional differences were generally not significantly different, once differences due to changing heights and diameters were controlled.

For the present merchantable volume requirements of the AFS, both functions which predict a merchantable ratio and simple taper functions are very accurate. Taper functions are slightly more precise.

The estimation of defect volumes was assessed using regression analysis with discrete variables such as species, and continuous variables such as age. The regression model developed in this analysis was significant in reducing the variance of defect percentages, however R^2 values were not over 40 percent.

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List of Abreviations Used

AFS	Alberta Forest Service
VSR	Volume Sampling Region
FORTRAN	FORTRAN IV computer language
TMA	Tree Measurement Analysis, a FORTRAN computer program.
DBH	Diameter outside bark at Breast Height (1.3 metres).
i.b.	inside bark.

1. Introduction

The accurate estimation of stand and forest tree volumes is largely dependent on the accuracy of individual tree volume estimation. In Alberta, the change from imperial to metric units of measure, coupled with the implementation of a new province-wide forest inventory resulted in a need for new individual tree volume functions. Also, the recent development of computer technology meant that more precise equations could be calculated.

This research project was initiated to review and assess the methods for estimating total, merchantable, and defect volumes. The project was established with the cooperation and support of the Alberta Forest Service (AFS), Timber Management Branch. Data were collected as part of the current Phase III inventory program, under the jurisdictions of the AFS and the Resource Evaluation and Planning Branch (REAP). Four regions and major commercial species of those regions were included in the study. The regions represented a variety of forested ecosystems across Alberta.

For total tree volume, or volume of the main stem from ground to tree tip, various local and standard volume functions were tested for accuracy. In addition, the variation between species, and between Volume Sampling Regions (VSRs) was assessed.

Merchantable volume was defined as the volume of the main stem within utilization specifications. Models tested for estimating this type of volume were either 1) functions

which estimate the ratio of merchantable volume over total volume or 2) mathematical integrations of functions which express stem form.

Two product types, pulp and sawlog, were differentiated for internal defect volume analysis. A cull study was used to determine the amount of saw and pulp defect in the sample trees. The estimation of each type of defect volume was reviewed by developing and testing a regression model, using both discrete and continuous variables. To develop the model, the discrete variables, species, cull suspect class, and region, were individually tested to determine whether they significantly improved the regression. Age and DBH, continuous variables, were also tested for significance.

The assessment of alternative methods for estimating each type of tree volume was based on statistical procedures including regression analysis, analysis of variance, and multiple comparison analysis. Methods presently in use by the AFS for estimating the three types of volume were included in this study.

2. Tree Volume Data--Source and Scope

2.1 Collection of Tree Volume Data

Tree volumes were obtained by cutting felled sample trees into short lengths and determining the volume of each section using geometric formulae. Approximately 4500 samples were collected by the Alberta Forest Service from four VSRs of the province:

VSR 3. Rocky Highland. Rocky-Clearwater Region, high elevation. 662 trees.

VSR 2. Rocky Lowland. Rocky-Clearwater Region, low elevation. 1087 trees.

VSR 4. Centre. Whitecourt-Slave Lake Region. 1023 trees.

VSR 8. Northeast. Lac La Biche-Athabasca Region. 1795 trees.

The boundaries of the four VSRs were predetermined by the AFS using elevation, climate, and topography as well as other criteria for differentiation (Figure 1).

Sample trees were located on either fixed or variable area plots. The allocation of these plots was systematic (fixed area plots) or stratified by AFS timber type (variable area plots) (Alberta Forest Service, 1981b). The fixed area plots correspond to Large Scale Photo plots; the variable area plots are also temporary sample plots for stand volume estimation (Alberta Forest Service, 1981a).

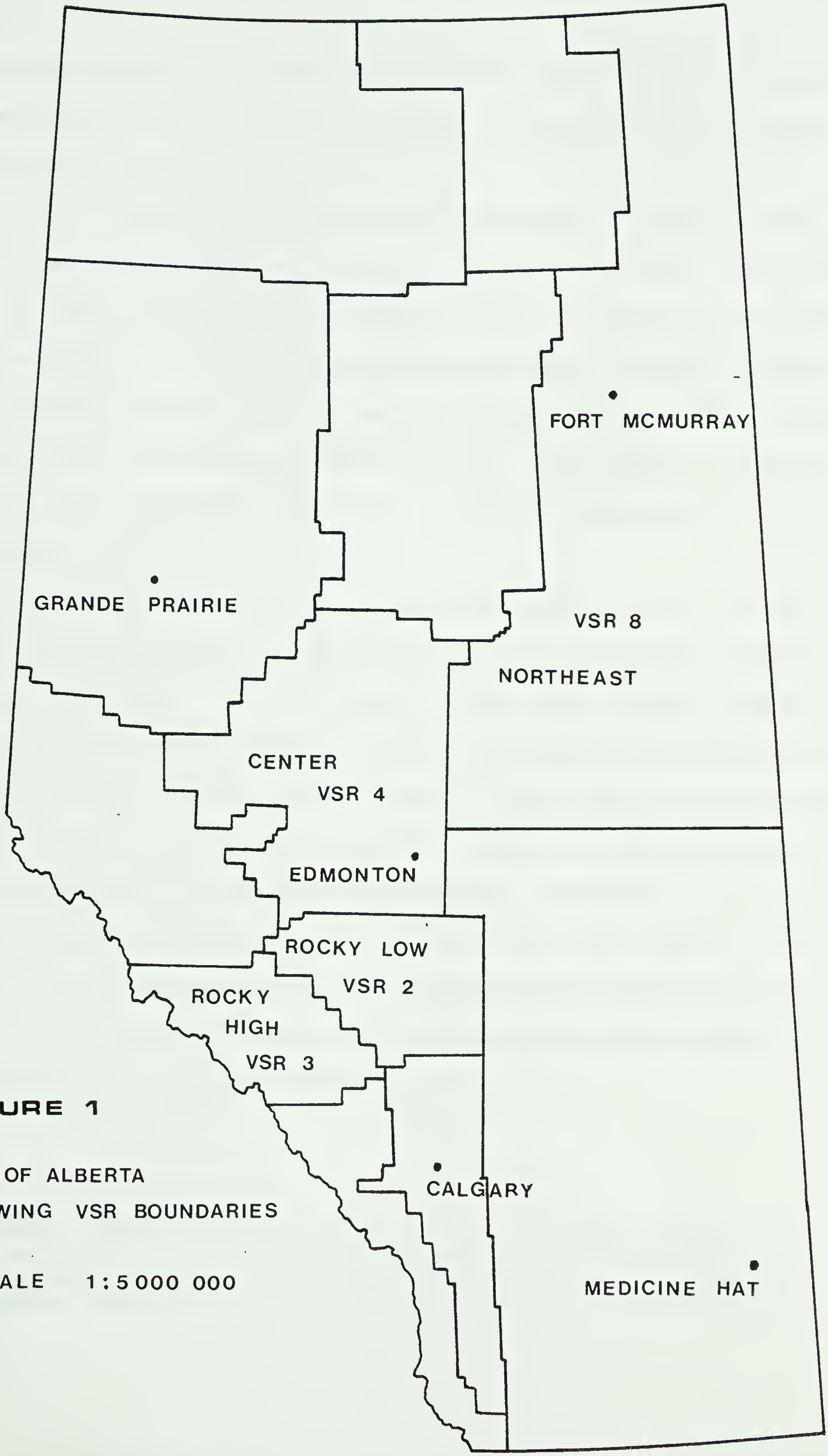

FIGURE 1

MAP OF ALBERTA
SHOWING VSR BOUNDARIES

SCALE 1:5 000 000

The distribution of plots was assumed to be random, although some bias may have occurred through greater sampling of more accessible areas.

All trees 1.1 centimetres[1] and greater at DBH, within the tree section plot were felled. Most of the tree section plots were variable area plots; hence, the distribution of diameters is slightly skewed, because larger diameters have a higher probability of being sampled (Smith, 1973). The advantage to this type of selection is that more valuable trees (i.e. larger DBH) will be better represented in the samples.

For all trees in a tree section sample plot, the DBH, species, and location parameters were recorded (Alberta Forest Service, 1981a). Each tree was then felled, and cut into short lengths (Figure 2). The first section was at 0.3 meters above ground (stump height), the second section was at 1.3 metres above ground (breast height), and the third section was at 2.8 metres above ground. Successive cuts were at 2.5 metre intervals up to the tree tip. All major limbs were cut in forked trees. For each section, diameter inside bark at the top of the section, the section length, and the dimensions of internal defect were recorded.

----

[1]Because both metric and imperial measures were taken, the following soft conversions were used: 1.1 centimetres= 0.4inches; 1.3 metres (breast height)=4.5 feet; 2.5 metres (section length)=8.0 feet;0.30 metres (stump height)=1.0 foot.

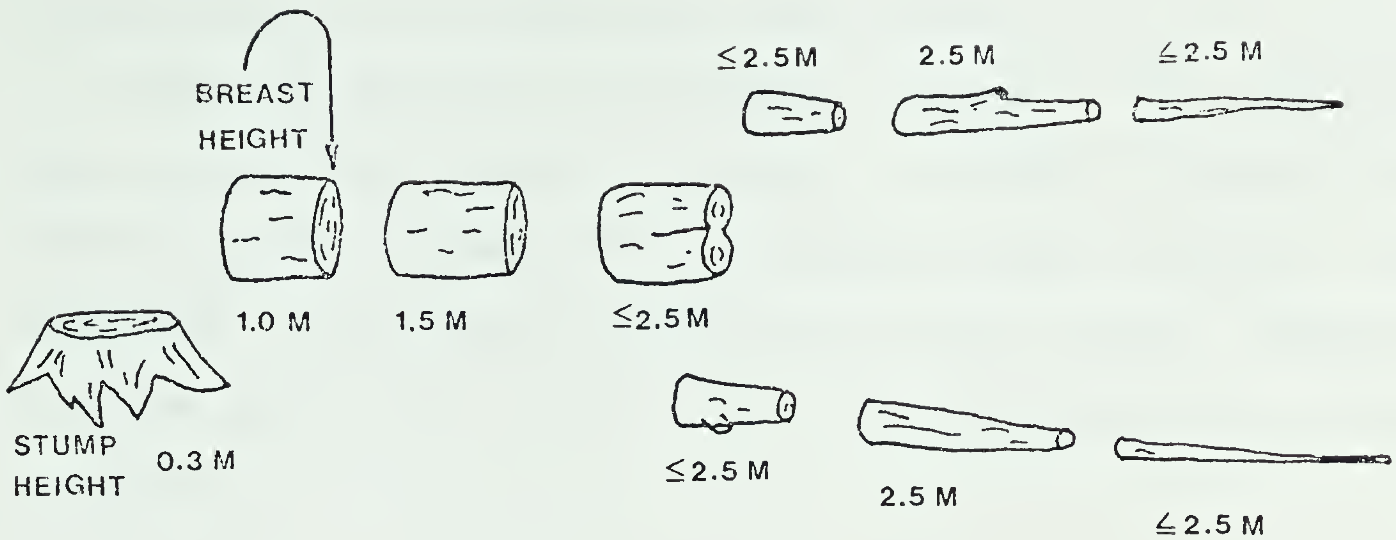

Figure 2. Pictorial Representation of Tree Sectioning Procedure

Sections with internal defect were further cut to determine the length of the defect.

Because of the long sampling period (from 1973 to 1981), two types of tally sheets were used in recording tree section data. For trees sectioned after 1977, additional information such as diameter outside bark at the top of each section was recorded (Appendix I); also, the advent of metrification in Canada resulted in a change in field records from imperial to metric units. Hence, all data had to be standardized into a similar format and all imperial data converted to metric. Computer programs were designed to reorganize the data, converting information to metric where necessary. (Appendix II, Flow chart of Computer Programs).

2.2 Calculation of Individual Tree Volumes

Once the data were keypunched, edited, and rewritten into a standard metric format, a FORTRAN (Cress *et al.*, 1970) computer program, TMA (Tree Measurement Analysis) was developed to provide the individual tree volumes. Geometric formulae were used to calculate total, merchantable, and net volumes.

2.2.1 Total Tree Volume

Total volume for each tree was calculated by summing section volumes using Smalian's formula (paraboloid frustrum) for the main bole sections, conical formula for the top section and cylindrical formula for the stump section.

Smalian's $$\frac{h}{2}(A_b + A_u) = V$$

Conical $$\frac{h}{3}(A_b) = V$$

Cylindrical $$h(A_u) = V$$

where V is the volume of the section (m^3)

A_b is the cross-sectional area at the base of the section (m^2)

A_u is the cross-sectional area at the top of the section (m^2)

h is the section length (m)

(Husch *et al.*, 1972)

The use of the three formulae was requested by the AFS. Many other studies have used the same equations in calculating

total tree volume (Burkhart, 1977; Beagle, 1974; Brown, 1934); Husch and others (1972) show this to be an adequate representation of the volume of the tree. Some overestimation can occur when Smalian's equation is used to calculate volume over a long section length. Husch and others (1972) cite a study which showed a 9.0 percent overestimation in volume using Smalian's equation on 8 (approximately 2.5 metre) to 16 foot lengths. The advantage in using Smalian's equation, though, is that the parameters required in calculation are easily measured.

2.2.2 Merchantable Volume

Merchantable volume is the volume of the tree within specified utilization limits. Four specifications were provided by the AFS for merchantable volume.

1. From a 0.30 metre stump to a 7 cm top diameter(i.b.)
2. From a 0.30 metre stump to a 10 cm top diameter(i.b.)
3. From a 0.30 metre stump to a 13 cm top diameter(i.b.)
4. From a 0.30 metre stump to a 15 cm top diameter(i.b.)

The TMA computer program simulates cutting of the tree at the stump (base cutoff point) and at the top (top cutoff point). The cutoff points specified by the AFS were a height cutoff at the base and a minimum diameter cutoff at the top of the stem.[2]

---

[2] The TMA program was designed to use either a height or diameter at both the top and base cutoff points for future use.

In cases where the cutoff point fell within a section, interpolation was used to estimate length and diameter for that sub-section. For the base cutoff point the following formulae were used:

$$TSEC = SUM\ SECL - \text{Base cutoff point(Stump height)} \quad (1)$$

$$DBASE = SQRT \quad DIB^2_{top} - \frac{(DIB^2_{top} - DIB^2_{base})}{SECL/TSEC} \quad (2)$$

where DBASE is the diameter(i.b.) at stump height(cm)
DIB_{top} is the d.i.b. at the top of the section(cm)
DIB_{base} is the d.i.b. at the base of the section(cm)
TSEC is the length of the interpolated section(m)
SECL is the section length(m)
SUM SECL is the sum of the sections to the top of the section to be interpolated(m)
Stump height is in metres
SQRT is the square root.

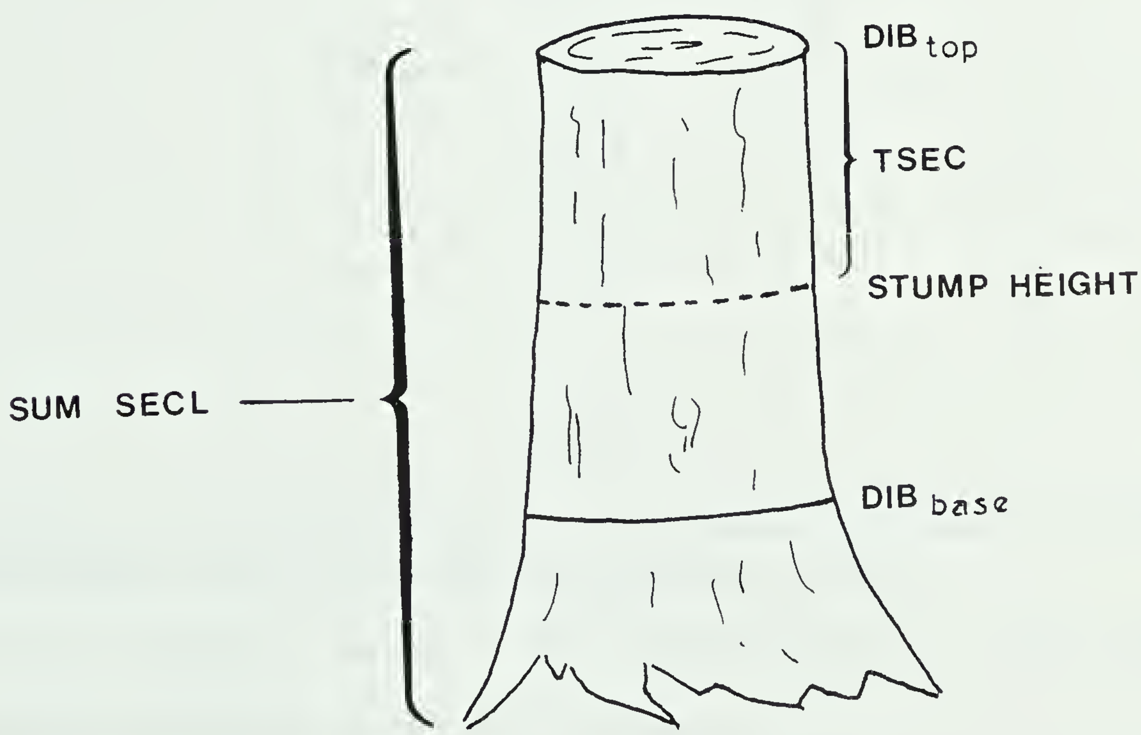

Figure 3. An Illustration of Parameters Used in Calculating the Volume Above the Base Utilization Standard

To interpolate length to the top cutoff point, the following equation was used:

$$TSEC = SECL \times \frac{(DIB^2_{base} - DTOP^2)}{(DIB^2_{base} - DIB^2_{top})} \qquad (3)$$

where DTOP is the specified minimum top d.i.b.(cm)
All other variables as in Equation 2.

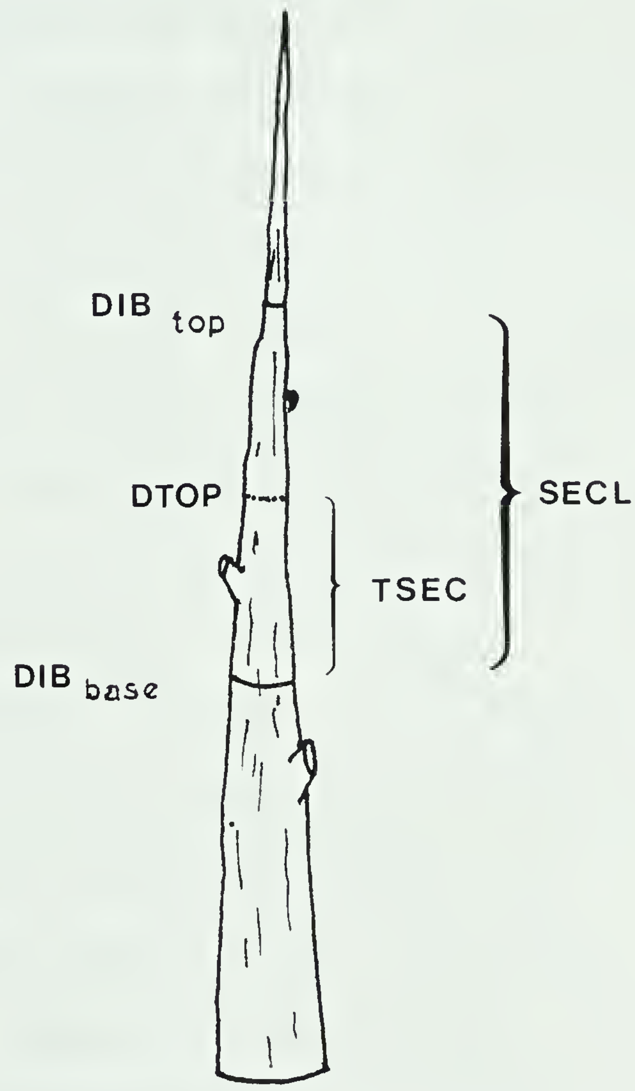

Figure 4. An Illustration of Parameters Used in Calculating the Volume Below the Top Utilization Limit

Section volumes below the stump height, and above the minimum diameter were set to zero.

2.2.3 Defect Volume

Internal defect volume was calculated by section for two product types, pulp and sawlog. For both types, the Alberta Scaling Manual (1979) was used as a guide in determining the defect volume for each type. Because the pattern of defect varies greatly, a hand-held electronic calculator was used for more subjective calculations.

Internal defect for sawlog products (sawlog defect) was calculated by taking a rectangular cross-sectional area of defect in square metres, and multiplying by the section length (metres). For the stump section, the cross-sectional area of defect at the top of the stump was used in calculating the section defect volume. For the second and third sections, the larger of the defect area at the base of the second section, or at the top of the third section, was projected through both of the lengths to simulate a 2.5 metre log. Defect volumes in subsequent sections were assessed by taking the larger of the squared defect area at the base or at the top of the section, and multiplying by the length of the defect. A two centimetre (or one inch) allowance was added to the actual dimensions of defect tallied on the field records as allowable loss in sawlog production (Alberta Forest Service, 1979).

For pulp products, allowable loss was calculated using Smalian's equation when defect extended through the section, otherwise the actual length of the defect was used with an equation for calculating the volume of a paraboloid. Again,

this method is similar to log scaling procedures.

For each of the defect categories, pulp and sawlog, net volumes were calculated:

1. From ground to tree tip (net total pulp and sawlog volumes).
2. From 0.3 metres above ground to 7.0, 10.0, 13.0, and 15.0 cm top diameter inside bark (net merchantable pulp and sawlog volumes).

When the base or top cutoff point fell within a section, defect volume was estimated using the following formulae:

$$DRAT = \frac{(DIB^2_{top} + DBASE^2 \text{ or } DTOP^2 + DIB^2_{base}) \times TSEC}{(DIB^2_{top} + DIB^2_{base}) \times SECL} \qquad (4)$$

$$DEFECT_R = DRAT \times DEFECT\ (pulp/saw)$$

where:

$DEFECT_R$ is the defect volume for the reduced section(m^3)

DRAT is a ratio of volume for the reduced section, to total section volume

All other variables as defined for Equation 2.

Section net volumes were calculated by subtracting defect from gross volumes. Because the squared defect method was used for sawlog defect, some sections had more defect volume than gross volume; net saw volume was set to zero for these sections. Section net volumes were totaled to yield net total and merchantable tree volumes.

2.3 Distribution of Data

Table 1 shows the distribution of all samples by species and VSR. Only those VSR/species groups of 25 or more samples were included in testing. Even though, for some species, the combination of all VSRs would have resulted in over 25 samples, the analysis was not attempted for the following reasons:

1. As more areas and/or more species are combined in a sample unit, the variance increases so a greater number of samples is needed for equal accuracy.
2. Analysis often required the separation of data by species, VSR, or by species and VSR combined. Since these sample groups would not be represented well when separated by these descriptors, the groups were initially deleted for simplicity.

Table 1. Distribution of sample trees by region and by species.

Species	**VSR 3**	**VSR 2**	**VSR 4**	**VSR 8**	**Totals**
White spruce *Picea glauca* (Moench) Voss	192	108	270	463	1033
Black spruce *Picea mariana* (Mill.) B.S.P.	68	278	166	279	791
Balsam fir *Abies balsamea* (L.) Mill.	9	8	64	18	99
Pine *Pinus banksiana* Lamb. *Pinus contorta* var. *latifolia* Engelm.	352	477	311	438	1578
Aspen *Populus tremuloides* Michx.	41	139	167	496	843
White birch *Betula papyrifera* March.	0	9	19	21	49
Larch *Larix laricina* (Du Roi) K. Koch	0	4	0	2	6
Balsam poplar *Populus balsamifera* L.	0	64	26	78	168
Totals	662	1087	1023	1795	4567

3. Total Volume Estimation

3.1 Introduction

Tree volume is strongly related to DBH, total height, and form. Models developed for estimating total volume have been of three forms: (Loetsch *et al.*, 1973)

METHOD 1: V=f(DBH)

METHOD 2: V=f(DBH,HT)

METHOD 3: V=f(DBH,HT,F)

where V is the volume from ground to tip
DBH is the diameter outside bark at breast height
HT is the total tree height
F is a measure of form.

Volume as a function of DBH alone (Method 1) is usually only used for small areas where a reliable diameter-height relationship can be established and so, are called local volume equations (Husch *et al.*, 1972). For larger areas, prediction of total volume based only on DBH is not as accurate as the other modes of prediction; if equations are developed for a specific region and species group, an accurate function may result. The more popular method for volume estimation is to estimate volume using height and DBH (Method 2, standard volume equations). Heights must be measured in the sample, but this additional information produces a greater accuracy of prediction (Loetsch *et al.*, 1973).

The third method is potentially the most accurate, because three parameters are included in estimating volume. However, form measurements are difficult to obtain and may be time consuming at the field level (Burkhart, 1977). Behre (1927) suggested that the addition of form for volume prediction could result in functions useful for a larger area, or a greater number of species. On the other hand, form often does not add significantly to the estimate (Honer, 1965). Also, development of computer software to estimate parameters using least squares linear regression has minimized the time and effort needed to develop new functions for localized areas. Classification by species, and/or area along with Method 2 usually results in a sufficiently accurate model, and so measurements of form are not necessary. Because the inclusion of form probably would not significantly improve the volume estimate and the measurement of form is time consuming, Method 3 was not tested.

Many models have been developed to predict volume as a function of DBH or DBH and height. An assessment of existing models is needed to determine which model is most accurate in predicting total volume for the sample area.

> <u>Hypothesis 1</u>
> Within a method of volume prediction, no one model is consistently more accurate than other models.

Once models of the two methods are assessed, the local and standard volume function methods should be compared to

determine which method is most accurate for the sample data.

<u>Hypothesis 2</u>
Models based on DBH and height are not significantly more accurate than models based on DBH alone.

The way to stratify the data to obtain the best estimate is also of interest. Differences between species, within a VSR must be determined so that categorization of data best minimizes the variance of total volume.

<u>Hypothesis 3</u>
There is no significant difference in total volume between species once variation due to diameter, height, and regional differences is controlled.

The control of diameter, height, and regional differences helps to reduce variation due to these factors, and eases the interpretation of results for species differences. Differences between regions for a particular species must be determined.

<u>Hypothesis 4</u>
There is no significant difference in total volume between regions once variation due to diameter, height, and species differences is controlled.

If Hypotheses 3 and 4 are not rejected, for practical purposes, one volume function could be used for all species and regions.

All hypotheses, together, are designed to obtain the best estimate of total volume using models previously developed, and to reduce the error of this estimate by stratifying the total volume data.

3.2 Methods

3.2.1 Assessment of the Two Methods of Total Volume Prediction

Using the literature as a guide, two models were chosen to predict volume as a function of DBH.

MODEL 1 $V = a + b\ DBH + c\ DBH^2$
(Hohenadl and Krenn, in Loetsch *et al.*, 1973)

MODEL 2 $V = a\ DBH^b$
(Berhout, in Loetsch *et al.*, 1973)

transformed to:
$\log V = \log a + b \log DBH$ (Husch, 1963).

where DBH is the diameter outside bark at breast height(cm)
H is the total tree height(m)
V is the total tree gross volume(m^3)
a, b, c are coefficients.

These models were chosen because they were representative of the two general types of models. The first is a simple quadratic model. The second is a logarithmic transformation of variables used to reduce the heterogeneity of variance (Neter and Wasserman, 1974). Other studies have shown that the variance of volume increases with increasing DBH or total height (Cunia, 1964; Honer, 1965), so a logarithmic transformation may be beneficial.

Five models were chosen to predict volume from DBH and height.

MODEL 3 Schumacher's logarithmic volume (1933)
$V = a\ DBH^b\ H^c$

transformed to:
$$\log V = \log a + b \log DBH + c \log H$$

MODEL 4 Spurr's constant form-factor (1952)

$$V = a\ DBH^2H$$

MODEL 5 Spurr's combined-variable (1952)

$$V = a + b\ DBH^2H$$

MODEL 6 Honer (1965)

$$\frac{DBH^2}{V} = a + \frac{b}{H}$$

MODEL 7 Spurr's logarithmic volume (1952)

$$V = a(DBH^2H)^b$$

transformed to:
$$\log V = \log a + b \log(DBH^2H)$$

Models 3 and 7 are logarithmic transformations, originally developed so a least squares linear regression procedure could be used (Spurr, 1952). As with the logarithmic local volume function, the logarithmic transformation can also aid in reducing the heterogeneity of variance. Model 4 uses DBH squared times height, which is reportedly the best single independent variable for the prediction of volume (Honer, 1965). Model 5 is the equivalent of Model 4 except that the intercept is allowed to vary from the origin. A reciprocal transformation of variables was used by Honer (Model 6) to obtain a more homogenous variance. The model is relatively new and was chosen because it is associated with functions for prediction of merchantable volume. Models 3, 4, 5, and 7 have been tested extensively with other data sets and have proved accurate (Spurr, 1952; Schumacher, 1933; Ellis,

1978).

All seven models were tested for accuracy of volume prediction using the multiple linear regression subprogram of the Statistical Package for the Social Sciences (SPSS) computer software package (Nie *et al.*, 1975). Data were separated by species to reduce variation caused by species differences, as well as to introduce the possibility that a model was consistently better for one species than for another. Because the regression of logarithmic models results in a report of the standard error of the logarithm of volume, the standard error of volume was approximated using:

$$\text{SQRT}\ \frac{\text{SUM ((actual - predicted volume)}^2\text{)}}{\text{error degrees of freedom}} \qquad (5)$$

(Spurr, 1952)

where:
SQRT is the square root
actual volumes are the section tree volumes
predicted volumes are obtained by taking the antilog of the equation produced by linear regression of the transformed model.

This is only an estimate of the standard error of volume, but it can be used in a rough comparison to standard errors from other models. A similar procedure was used by Faurot (1977). The standard error for Model 6 was also approximated in this manner.

Models 3 and 7 were also fit using a nonlinear algorithm (British Columbia Forest Service, 1981) for one of the species. The estimated coefficients using the nonlinear

fit of the multiplicative model versus the linear fit of the logarithmic transformation were compared.

Hypothesis 1 was assessed by examining regression results of models within a particular method. The standard error values, actual or calculated, were compared. Within the logarithmic models, the adjusted R^2 values were compared; similarly, a comparison of the adjusted R^2 values for the two linear models was made.[3] With large sample numbers, the adjusted R^2 value approaches the R^2 value.

The logarithmic version of volume as a function of DBH (Model 2), and Schumacher's logarithmic volume function (Model 3) were compared as a test of Hypothesis 2. An alpha level of .05 was used to determine whether the addition of the logarithm of height significantly improved the model.

3.2.2 Species and Region Differences

The regression method for analysis of covariance (Neter and Wasserman, 1974) was used in testing Hypothesis 3. Models were developed with species and regions represented as indicator variables. For species differences, the following model was formed:

$$
\begin{aligned}
V = a &+ b\ DBH^2H + c\ Z_1 + d\ Z_2 + e\ Z_3 \\
&+ f\ Z_4 + g\ Z_5 + h\ DBH^2HZ_1 + i\ DBH^2HZ_2 \\
&+ j\ DBH^2HZ_3 + k\ DBH^2HZ_4 + l\ DBH^2HZ_5
\end{aligned}
$$

---

[3] The adjusted R^2 value is calculated by subtracting the ratio of the error variance to the variance of the total from one (Fowler and Bigelow, 1979).

$$(6)$$

where Z_1 = 1 for white spruce, else 0
Z_2 = 1 for black spruce, else 0
Z_3 = 1 for balsam fir, else 0
Z_4 = 1 for pine, else 0
Z_5 = 1 for aspen, else 0
All Zi = 0 for balsam poplar

DBH is the diameter at breast height(cm)
H is the total tree height.

For differences in region, the following model was used:

$$V = a + b\ DBH^2H + c\ X_1 + d\ X_2 + e\ X_3 +$$

$$f\ DBH^2HX_1 + g\ DBH^2HX_2 + h\ DBH^2HX_3 \qquad (7)$$

where X_1 = 1 for VSR 3, else 0
X_2 = 1 for VSR 2, else 0
X_3 = 1 for VSR 4, else 0
All Xi = 0 for VSR 8.

Both equations were fit using multiple linear regression. DBH squared times height was used as a covariate to account for variation due to diameter and height differences. Hence, remaining variation was attributed to differences in form between VSRs or species. For differences in species, data were separated by VSR and *vice versa*, for easier interpretation of results.

Once the equations were fit, Scheffe's method for contrasts (Neter and Wasserman, 1974) was used to test Hypotheses 3 and 4. The method was applied to differences in slope and differences in intercept coefficients, for contrasts between all possible pairs of species and then between all possible VSR pairs. For this method, the difference between coefficients is significant when:

$$\frac{B_i - B_j}{\mathrm{SQRT}\ (s^2_{B_i} + s^2_{B_j})} \geq S$$

(Neter and Wasserman,1974)

where:

$S^2 = (k-1)F_{(k-1),(n-k-1),alpha}$

SQRT is the square root

B_i, B_j are coefficients to be compared

k = the number of treatments

$s^2_{B_i}$, $s^2_{B_j}$ are the coefficient variances.

A confidence level of 95% was chosen as the test level; a level lower than this was not considered accurate, whereas a level higher than this would not be practical.[4] Although Scheffe's method is conservative relative to other tests, it is suitable for unequal numbers in a category, and many contrasts can be tested (Kleinbaum and Kupper, 1978).

3.3 Results

3.3.1 Local and Standard Volume Functions

The regression results for local volume functions are listed in Table 2a, and results for standard volume functions are in Table 2b. All coefficients were significant, except the coefficient associated with DBH in Model 1 for balsam fir and white spruce.

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[4]An alpha level of .05 was chosen for most tests completed in this project.

Table 2a. Results of regression analysis for total volume with DBH by species.

Species group	No. Trees	MODEL 1		MODEL 2	
		Adj. R^2	Se	Adj. R^2	Se
White spruce	1033	.92921	.15382	.96814	.21660
Black spruce	791	.88824	.03337	.93412	.04837
Balsam fir+	64	.94836	.05273	.97517	.09176
Pine	1578	.93060	.08343	.97182	.10069
Aspen	843	.94682	.09987	.97456	.12444
Balsam poplar++	168	.90983	.11360	.96208	.11683

\+ only VSR 4 represented
++ only VSRs 2,4 and 8

Table 2b. Results of regression analysis for total volume with DBH and height by species.

Species group	No. Trees	MODEL 3		MODEL 4		MODEL 5		MODEL 6		MODEL 7	
		Adj. R^2	Se	Adj. R^2	Se	Adj. R^2	Se	Adj. R^2	Se	Adj. R^2	Se
White spruce	1033	.93508	.15901	.98304	.10240	.97132	.09772	.77212	.11677	.99003	.09608
Black spruce	791	.96108	.02152	.96306	.02850	.95141	.02605	.74421	.02681	.96603	.01957
Balsam fir+	64	.99375	.03165	.99470	.02723	.98621	.02704	.93828	.03017	.99373	.02883
Pine	1578	.97729	.05137	.98731	.04978	.97689	.04880	.76570	.05395	.98917	.04854
Aspen	843	.91568	.10875	.96844	.10432	.94404	.10342	.66431	.10899	.98681	.10394
Balsam poplar++	168	.85764	.11630	.97869	.08343	.95268	.08343	.23261	.15418	.96809	.08463

\+ VSR 4 only
++ VSRs 2,4 and 8 only

NOTE: Se for all models are the standard errors for volume. The standard errors for Models 1, 2, 3, and 7 are empirical estimates of the standard errors (See text). The adjusted R^2 values are not all reported in the same units and so caution is necessary in comparing these values for different models.

For both of the local volume functions tested, all R^2 values were greater than 85 percent. The approximate standard errors calculated for the logarithmic model (Model 2) were consistently higher than the actual standard errors of the quadratic model (Model 1). Plots of volume versus DBH indicated that variance of volume increased with increasing DBH, as anticipated (Cunia,1964; Zar,1968). The logarithmic transformation yielded a more homogeneous variance of volume, and therefore a more uniformly distributed residual plot. Using a stepwise linear regression procedure, for the quadratic model, DBH^2 entered before DBH for all species; the addition of DBH to the regression was not significant for balsam fir and white spruce.

Each of the five models based on volume as a function of DBH and height were evaluated using multiple linear least squares regression. The comparison of standard errors (actual and calculated) indicated that Model 7 had the lowest values for each species. The ranking of the remaining models from lowest to highest standard errors was Model 5, then Model 4, followed by Models 3 and 6, together. The examination of residual plots with Spurr's two linear models indicated a departure from linear regression assumptions, in that the variance of the residuals was not homogeneous. The logarithmic transformation of Models 3 and 7 helped to provide a more homogeneous variance. Model 6 had comparatively low adjusted R^2 values, however this value applies to DBH squared over volume, rather than volume or

the logarithm of volume.

The nonlinear fit of Model 3 for aspen accounted for 94.381 percent of the variance (R^2) and for Model 7, 94.368 percent of the variance. The R^2 value was assumed to be comparable to the adjusted R^2 value reported for the linear regressions, because of the large sample number. The standard error for Model 3 was .10376, and for Model 7, .10381. A comparison of coefficients follows:

Model 3	a	b	c
linear	.0000808	1.97319	0.72159
nonlinear	.00005216	1.97396	0.87669

Model 7	a	b
linear	.0000377	0.98432
nonlinear	.00004345	0.97091

For Model 3, the coefficients from the linear fit of the transformed model were close in value to those from the nonlinear fit of the untransformed version. The power coefficients ('b' and 'c') were most similar. The 'a' coefficient was greater with the linear fit of the transformed model, indicating that the logarithmic model possibly predicts a higher volume than does the nonlinear model. However, the graph of actual to predicted volumes using the linear fit of the model was not visibly different than the graph of the actual to predicted volumes using the nonlinear version (Appendix III). With Model 7, the power coefficients were again similar, and the comparison of graphs of the two models showed no visible difference.

3.3.2 VSR and Species Differences

The results of tests using Scheffe's method for paired contrasts of slope and intercept coefficients, representing VSR and species differences, are listed in Tables 3 and 4.

Table 3 shows that four of six pairs of species in VSR 3, six of ten pairs in VSR 2, six of fifteen pairs in VSR 4, and two of ten pairs in VSR 8 had significantly different slope or intercept coefficients. White spruce was different from pine and aspen in all but VSR 8. Black spruce was different from pine and aspen in the two Rocky-Clearwater regions (VSR 3 and 2). Balsam poplar was different from pine and aspen for the three VSRs tested.

Table 4 is a list of S values for differences in total volume between VSR pairs, within a species group. Four of six pairs of VSRs for white spruce, four of six pairs for black spruce, four of six pairs for pine, two of six pairs for aspen, and none of the three pairs for balsam poplar were significantly different in total volume. VSRs 2 and 3 were not significantly different for any of the species tested. VSRs 3 (Rocky, high elevation) and 4 (Centre) were different for white and black spruce. VSR 3 and VSR 8 differ for black spruce and pine. VSR 2 and 4 were different for all species except balsam poplar. For pine, white spruce, and black spruce, the Rocky area, low elevation (VSR 2), varied from the Lac La Biche area (VSR 8). Finally, VSR 4 was different from VSR 8 for white spruce, pine, and aspen.

Table 3. Differences in total volume between species within a VSR.

Species group Paired Contrasts	VSR 3 S value		VSR 2 S value		VSR 4 S value		VSR 8 S value	
	Inter	Slope	Inter	Slope	Inter	Slope	Inter	Slope
White spruce vs Black spruce	0.3842	0.9998	1.2096	1.7996	2.3553	-2.8086	1.4849	-0.8306
White spruce vs Balsam fir	------	-----	------	------	1.9839	-3.4448*	------	-----
White spruce vs Pine	0.7128	-2.9871*	0.8056	-6.3429*	2.1444	-5.5902*	1.3850	-2.3755
White spruce vs Aspen	2.6325	-2.9849*	0.9624	-3.3814*	2.3946	-4.4673*	0.2539	-1.4324
White spruce vs Balsam poplar	------	-----	1.5308	-0.0291	3.5212*	-2.8971	1.7703	2.4890
Black spruce vs Balsam fir	------	-----	------	------	-0.2389	-0.2975	------	-----
Black spruce vs Pine	0.2925	-3.8951*	-0.4281	-6.9436*	-0.2341	-1.1980	-0.1376	-0.3055
Black spruce vs Aspen	1.9091	-4.1823*	-0.1813	-4.5221*	0.0369	-0.4067	-1.2424	0.1406
Black spruce vs Balsam poplar	------	-----	-0.1033	-2.2171	0.1447	1.6034	-0.3616	1.7052
Balsam fir vs Pine	------	-----	------	------	0.0200	-0.9326	------	-----
Balsam fir vs Aspen	------	-----	------	-----	0.2739	-0.0728	------	-----
Balsam fir vs Balsam poplar	------	-----	------	------	0.4517	2.2516	------	-----
Pine vs Aspen	1.7035	1.2396	0.2174	2.5255	0.2715	1.0731	-1.1355	0.8861
Pine vs Balsam poplar	------	-----	0.5020	8.9410*	0.4826	4.9212*	-0.1814	5.3344*
Aspen vs Balsam poplar	------	-----	0.1505	4.4676*	0.0928	3.4036*	1.4240	4.0812*

*significant at the .05 level

NOTE: Balsam fir was represented in only 1 VSR. *S value, intercept* is the S value for the difference in intercept coefficients. *S value, slope* is the S value for the the difference in slope coefficients.

Table 4. Differences in total volume between VSRs within a species group.

Paired Contrasts	White spruce S value		Black spruce S value		Pine S value		Aspen S value		Balsam poplar S value	
	Inter	**Slope**	**Inter**	**Slope**	**Inter**	**Slope**	**Inter**	**Slope**	**Inter**	**Slope**
VSR 3 vs VSR 2	-1.7692	1.0890	0.4924	0.8401	-1.8702	2.7838	-0.7542	0.4786	------	------
VSR 3 vs VSR 4	-3.7304*	1.3378	3.9845*	-7.1631*	1.0852	-0.9286	0.0207	-0.1933	------	-----
VSR 3 vs VSR 8	-1.0338	-2.2008	3.5868*	-7.7596*	1.4753	7.4370*	-1.2822	0.4637	-----	-----
VSR 2 vs VSR 4	-3.5949*	0.1783	4.3804*	-8.5315*	2.8313*	-3.8345*	1.1283	-2.9324*	0.5963	-1.6057
VSR 2 vs VSR 8	133.7118*	-4.3420*	4.7351*	-10.3438*	4.2461*	5.2763*	-0.6647	-0.1239	0.3414	-0.4083
VSR 4 vs VSR 8	4.4004*	-5.7129*	-1.9328	2.3706	-0.1580	8.7503*	-2.4764	4.7221*	-0.4889	1.6817

* significantly different at the .05 level

NOTE: Balsam fir was represented in only 1 VSR. *S value, intercept* is the S value for the difference in intercept coefficients. *S value, slope* is the S value for the the difference in slope coefficients.

3.4 Discussion

3.4.1 Local Volume Functions

Of the two models assessed, the standard error values were lower for Model 1; the comparison of these standard errors, though, is not unbiased. The residual pattern for Model 1 indicated a nonhomogeneous variance, a departure from linear regression assumptions. The logarithmic transformation helped to reduce the variance for larger volumes and so the resulting residual patterns indicated a more homogeneous variance. The logarithmic model would, then, be the recommended model, even though the calculated standard error was higher than the standard error for Model 1, the quadratic model. The heterogeneity of variance must be ignored if Method 1 is to be employed. A nonlinear fit of Model 2 would be desirable, because the actual rather than the transformed values are minimized in the regression procedure.

3.4.2 Standard Volume Functions

Standard volume functions tested were of three forms:

1. Linear (Models 4 and 5).
2. Logarithmic or reciprocal transformations to a linear form (Models 3, 6 and 7).
3. Nonlinear (Models 3 and 7).

Comparing the standard error values, the linear models have been proven accurate in volume prediction. Model 4 which

forces the regression through zero had similar standard errors and adjusted R^2 values to Model 5 in which the intercept was allowed to vary. The unexpected higher adjusted R^2 values reported for Model 4 were probably the result of the forcing the model through zero (Gordon, 1981). The standard errors, however, showed the expected result in that Model 5 yielded slightly lower standard error values. The advantage to the model forced through zero, is that the expected result of zero volume with zero DBH and height is predicted.

Of the transformed models, Honer's model, which uses a reciprocal transformation, had low adjusted R^2 values, although the adjusted R^2 values were reported for the ratio of DBH squared over volume. The calculated standard errors for Model 6 were similar to those calculated for Model 3. However, Honer's model does require more manipulation of variables to obtain the volume estimate than does any of the remaining models tested, and does not provide a great deal more accuracy. Model 7, Spurr's logarithmic model, consistently yielded higher adjusted R^2 and lower approximate standard error values than did Model 3 (Schumacher's). The model approximates a cone shape for the tree (DBH squared times height), with additional variation in form being accounted for by the variation in coefficients.

Both nonlinear models produced high R^2 values and low standard error values for aspen, the only species tested.

The R^2 values were almost identical for the two models. The nonlinear version of Model 3 should be slightly better in estimating volume as an additional parameter is allowed to vary than with Model 7. The proximity of results for the two models then, indicates that very little is gained by allowing the variation of both power coefficients.[5] Further testing of the two nonlinear models for other species was not attempted. However, the indication, from testing the logarithmic transformations of the models is that both models yield accurate results over all species.

The disadvantage of linear models as a group is that volume has unequal variance, and hence the assumptions for linear regression are not met (Honer, 1965). The use of weighted least squares regression has been suggested (Cunia,1964); the problem with this is that weights must be known or estimated (Kleinbaum and Kupper, 1978). If the problem of unequal variance is overlooked, Models 4 and 5 yield high R^2 values. Indeed many authors have used these functions to estimate volume (Burkhart, 1977; Myers and Edminster, 1974; Beagle, 1974; Bruce and Demars, 1974).

The use of transformations of variables is advantageous in that a more homogeneous variance can result (Zar, 1968), and also a least squares regression method can be used

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[5]The logarithmic transformations behave differently in that Model 7 provided more accurate results than Model 3. This is because the logarithmic transformation changes the number of dependant variables for Model 3 from 1 to 2 variables. The results expected with the nonlinear versions are then not applicable to the transformed versions of these same models.

(Schumacher, 1933). However, the square of the difference between transformed actual and predicted dependent variables is minimized rather than the untransformed values (Zar, 1967). Also, the standard error that is reported is the standard error of the transformed variable, and hence comparisons and confidence limits are difficult to interpret (Cunia, 1964). The standard error of volume can be approximated, however, some bias is introduced in this calculation (Spurr, 1952). The empirical R^2 values could also be calculated for the transformed models and used for comparison.

The nonlinear fit of Spurr's or Schumacher's model is the superior mode of volume estimation. For this study, the results for aspen are very accurate. Also, the advantages of using the nonlinear fit of models are:

1. The nonconstant variance of volume is not a problem.
2. The square of actual minus the predicted volumes is minimized, rather than the transformation of values.
3. The reported standard error is the standard error of the volume (Husch *et al.*, 1972; Zar, 1968).

The increasing availability of computer programs to approximate the nonlinear fit has made this solution more feasible (Husch *et al.*, 1972).

3.4.3 Comparison of Local and Standard Volume Functions

The applicability of each of the two methods of volume estimation was assessed. The addition of height (Schumacher's model) to the logarithmic model of volume as a function of DBH was significant over all species. Hypothesis 2 was therefore rejected, and so the result that volume as a function of DBH and height is a significantly better method of volume prediction was concluded. The addition of polynomial terms into the regression of volume predicted by DBH, would have accounted for a greater portion of the variation, however the returns dimish with each higher polynomial (Kleinbaum and Kupper, 1978). Even with the quadratic model, for two of the six species tested, the addition of DBH, after DBH^2, was not significant. Also, the addition of height permits the use of the equation for areas of differing height-diameter relationships. In total, Method 1 accounts for a large portion of the variance, but for large land bases, volume inventories based on diameter and height are suggested (Husch *et al.*, 1972; Loetsch *et al.*, 1974).

3.4.4 VSR and Species Differences

Hypothesis 3 could not be wholly rejected, as very few species pairs were different in total volume in VSR 8. In the remaining three VSRs, approximately half of the species pairs varied in total volume. Hypothesis 4 was rejected for white spruce, black spruce, and pine. However, for aspen and

balsam poplar, the conclusion that regions are different in total volume could not be inferred. Spurr (1952) concluded that species differences were more significant than regional differences. For this data set it appears that pairs of regions tested were more significant in defining variation in total volume. The use of Scheffe's method gives conservative results, but the method is commonly used, and the magnitude of values produced indicate that similar results would be obtained using other methods. Schumacher (1933) concluded that differences in total volume between species were mostly due to different diameter-height relationships; DBH squared times height, as a covariate term, greatly reduced the variation of volume.

3.5 Conclusion

Overall, standard volume functions are more accurate than local volume functions. Local volume functions could be adequate for small locales of homogeneous diameter-height combinations. Of the standard volume functions, the nonlinear models are the first choice for volume estimation (Ellis, 1978; Husch *et al.*, 1972). Transformation of these nonlinear models for use with a linear regression method also gives accurate results. If the assumption of equal variance is ignored, linear models can be used with accurate results.

Once the variation in volume due to different diameter and height combinations is accounted for, very little variance remains and hence few species and regions were different in total volume. Based on the paired differences, the following breakdown should be used to minimize the variance of total volume most efficiently. Generally, VSRs 2 and 3 can be combined for estimation. In all VSRs, the two spruce species should be separated from pine. Aspen should be estimated separately from other species; estimates made for VSR 4 or VSR 8 can be used in the Rocky area, although VSR 4 estimates should not be used for VSR 8 and *vice versa*. Balsam poplar should be estimated separately from other species including aspen, although one volume function can be used for all of the three regions tested.

4. Merchantable Volume

4.1 Introduction

Merchantable volume is the portion of the main stem tree volume within specified utilization limits. Separate functions can be developed for each utilization standard, although these functions are often incompatible (Burkhart, 1977; Belanger and Cleroux, 1973). An equation which estimates merchantable volume for many standards, simultaneously, is more desirable. Functions for prediction of merchantable volume must be flexible for a wide range of utilization standards and must predict total volume equal to that predicted by the total volume function being used.

Generally, two types of simultaneous estimation have been used (Cao *et al.*, 1980; Loetsch *et al.*, 1973). The first involves multiplying total volume by a factor less than one (merchantable ratio (MR)). The factor is estimated using regression analysis where:

$$MR = \frac{\text{Merchantable Volume}}{\text{Total Volume}} = f(DBH,H,h,d,\ldots)$$

where:
- DBH is the diameter outside bark(cm) at breast height(1.3m)
- H is the total tree height (m)
- h is the merchantable height (m)
- d is the diameter inside bark(cm) at 'h'.

The second method is the mathematical integration of a taper equation over the merchantable portion of the tree (Max and

Burkhart, 1976).

Because the merchantable ratio is multiplied by total volume to obtain merchantable volume, the estimation of merchantable volume using this method is dependent on the accuracy of both the merchantable ratio and total volume function. Also, the regression estimate of the merchantable ratio rather than merchantable volume is obtained. The advantage of merchantable ratio functions is that they are easily integrated into an existing system for predicting total volume (volume-based system), and generally the equations are not complex.

The advantage of the taper function method is that any combination of lower and upper limits can be used, and also taper models can be used independently of total volume functions (Martin, 1981). In addition, the merchantable height, merchantable volume, total volume, and top diameter are all estimated using one model. The disadvantage of taper functions is that they are often complex. In addition, if a volume-based system is already established, the adoption of taper functions may require the development of a totally new system for volume estimation (Cao *et al.*, 1980).

An assessment of representive models for each of the two methods to determine which are appropriate for Alberta is needed.

> Hypothesis 6
> Within a particular method, there is no significant difference in prediction accuracy between models tested.

The most accurate of the taper models and merchantable ratio models can then be compared.

Hypothesis 7
There is no significant difference in the accuracy of the two methods for merchantable volume estimation.

The accuracy of the models in predicting the merchantable volume, as well as the computational ease, and compatibility with the present system must all be considered in the assessment.

4.2 Methods

Representative models were needed for testing. Five models were chosen which predict the merchantable ratio.

1. Honer's height ratio (1964).

$$MR = a + b\,\frac{HTOP}{HT} + c\,\frac{(HTOP)^2}{(HT)^2}$$

2. Honer's squared diameter ratio (1964).

$$MR = a + b\,\frac{(DTOP)^2}{(DBH)^2} + c\,\frac{(DTOP)^4}{(DBH)^4}$$

3. Honer's squared diameter ratio, corrected for stump height (1974).

$$MR = a + b\left(\left(1+\frac{hs}{HT}\right)\left(\frac{DTOP^2}{DBH^2}\right)\right) + c\left(\left(1+\frac{hs}{HT}\right)\left(\frac{DTOP^2}{DBH^2}\right)^2\right)$$

4. Honer's diameter-height ratio (1974).

$$MR = a + b \frac{DTOP}{DBH} + c\,(1 - \frac{HTOP}{HT})^2$$

5. Alberta Forest Service, modified Honer's (Lowe, 1981).

$$MR = a + b((1 - \frac{hs}{HT})^2 - (\frac{DTOP}{DBH})^4) + c((1 - \frac{hs}{HT})^2 - (\frac{DTOP}{DBH})^4)^2$$

where:
HTOP is the height above ground to merchantable limit
HT is the height from ground to tip
DBH is the diameter outside bark at breast height
DTOP is the diameter inside bark at the merchantable limit
hs is the stump height.

Each model was assessed using multiple linear regression by species. Almost all of the functions tested were developed by Honer; the models also are related in that Model 3 is an adaptation of Model 2 to vary stump height. However, few other models have been developed, and Honer's model has been tested with other data sets (Ker, 1974; Cao *et al.*, 1980). A nonlinear model developed by Burkhart (1977) was shown by Cao and others (1980) to be more accurate than Honer's height ratio and diameter-height ratio functions (Models 1 and 4). Burkhart's model, though, is intrinsically nonlinear and so a reliable nonlinear regression algorithm is required. More important, the model does not have a provision for changing stump heights; the only independent

variable is minimum diameter at the top divided by DBH. Because of these reasons, Burkhart's model was not tested.

The mathematical integration of taper functions, the second method, was also tested using multiple regression analysis. Two models were chosen based on accuracy and useability. The first model chosen is a model developed by Kozak and others (1969). The model is basically a quadratic equation, conditioned so that when merchantable height equals total height, the predicted squared diameter ratio (d^2/DBH^2) is zero. This model was previously used by the British Columbia Ministry of Forests, and was just recently replaced by a segmented polynomial equation (Demaerschalk and Kozak, 1977; Demaerschalk, 1981; Kozak *et al.*, 1969).

MODEL 6 Kozak and others (1969)

$$\frac{d^2}{DBH^2} = b\left(\frac{h}{H} - 1\right) + c\left(\frac{h^2}{H^2} - 1\right)$$

$$h = \frac{(-bH) - \text{SQRT}\left((bH)^2 - 4c(aH^2 - d^2H^2)/DBH^2\right)}{2c}$$

$$MV = kDBH^2\left(a(h-hs) + b\left(\frac{h^2-hs^2}{2H}\right) + c\left(\frac{h^3-hs^3}{3H^2}\right)\right)$$

where $a = -b - c$
a, b, c are coefficients
k is .00007854 for estimates in metric units
hs is the stump height
h is the merchantable height
H is the total tree height
d is the minimum diameter(i.b.)
MV is the merchantable volume.

A model developed by Omerod (1973) was also tested. This model is nonlinear, conditioned so that zero is predicted as

the minimum top diameter when the merchantable height equals the total height. When the merchantable height is breast height (1.3 metres), the minimum top diameter predicted is equal to the DBH. The model was transformed using logarithms so that a linear regression procedure could be employed.

MODEL 7 Omerod (1973)

$$\frac{d^2}{DBH^2} = ((H - h)/(H - 1.3))^{2b}$$

transformed to:

$$\log \frac{d^2}{DBH^2} = 2b \log((H-h)/(H-1.3))$$

$$h = H - ((d/DBH)^{1/b} (H - 1.3))$$

$$MV = \frac{(kDBH^2)(1.3 - H)}{(2b+1)} \times \left(\left(\frac{h - H}{1.3 - H}\right)^{2b+1} - \left(\frac{hs - H}{1.3 - H}\right)^{2b+1} \right)$$

All variables are as those in Model 6, above.

For both models, then, the squared diameter ratio is predicted by a function expressing tree taper. This function is reorganized to obtain merchantable height, and integrated for merchantable volume (MV).[6]

Multiple linear regression analysis by species was implemented to determine coefficients for the functions which estimate d^2/DBH^2. These coefficients were then used to determine the estimated merchantable height and merchantable volume. The calculated merchantable height (actual) was then

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[6] Merchantable heights must only be measured to fit the equation for estimating the squared diameter ratio.

regressed against the estimated merchantable height (predicted) by species, to determine how well the fitted equation predicted merchantable heights. Similarily, the merchantable volume, actual and predicted, was regressed by species.

Testing of other models describing tree taper could not be accomplished within the time period allowed for this project. More complex models, such as the segmented polynomial model proposed by Max and Burkhart (1976) were not selected for testing because:

1. Less complicated models, if accurate, are advantageous. If one or both of the models tested here proved accurate, the adoption of more complicated models is not practical.
2. Segmented models require the identification of inflection points, which may be difficult to define.

Because of the initial calculations of merchantable volume, volumes used for testing all models were variable only in top diameter. Stump heights were not varied (See Section 2.2.2). The merchantable volumes used in the study were then representative of the present AFS stump utilization standard. Also, only those trees of 2.5 metres in length and greater, within the specified limits, were included.

4.3 Results

4.3.1 Merchantable Ratio Method

Merchantable ratio models as a function of variables including merchantable height (Models 1 and 4) were consistently more accurate (higher R^2, lower standard error) than models which do not include merchantable height as a variable (Table 5). Model 3, which is a modification of Model 2 to include stump height, did not estimate merchantable ratio substantially better. Models 3 and 5 were similar in accuracy of prediction over all species groups.

Models 1, 2, and 4 do not include stump height as a variable. The fitted equations, then, are useful only in predicting merchantable volume for the fixed stump height represented by the original sample; a change in stump height is not reflected in the predicted merchantable ratio. The fitted equations for Models 3 and 5 yielded different merchantable ratio values for changes in stump height; however, Model 3 did not respond to changing stump heights if the minimum top diameter was set to zero.

Each model was tested to determine if a value of one was predicted for total volume (merchantable ratio of one).

Model 1--A value of .92991 was predicted as the lowest merchantable ratio for black spruce and .96354 predicted for pine as the highest value.

Model 2--The range of predicted values was .9737 for white spruce to 1.0048 for black spruce.

Table 5. Results of linear regression of merchantable volume models by species.

Species group	MODEL 1		MODEL 2		MODEL 3		MODEL 4		MODEL 5	
	R^2	Se	R^2	Se	R^2	Se	R^2	Se	R^2	Se
White spruce	.96347	.02418	.90643	.03870	.90604	.03878	.95788	.02597	.90747	.03849
Black spruce	.90309	.05110	.78836	.07552	.78588	.07596	.89809	.05240	.78297	.07647
Balsam fir+	.97816	.02158	.94973	.03283	.94832	.03328	.97452	.02337	.93988	.03590
Pine	.95357	.03150	.87671	.05132	.87632	.05140	.95447	.03119	.87978	.05068
Aspen	.97472	.02392	.90226	.04703	.90174	.04715	.96973	.02617	.90718	.04583
Balsam poplar++	.95366	.02762	.85231	.04931	.85293	.04921	.94202	.03090	.85854	.04826

\+ VSR 4 only
++ VSRs 2, 4 and 8 only

NOTE: The Se reported is the standard error for the merchantable ratio.

Model 3--The range of predicted values was .9740 for white spruce to 1.0045 for black spruce.

Model 4--A value of .9830 was estimated for white spruce to a value of 1.0063 for pine.

Model 5--The range of predicted values was .9939 for white spruce to 1.0235 for black spruce.

The significance of the variation from one was not tested; the fact that the models did not predict an exact value of one was considered only.

4.3.2 Taper Models

Kozak's model predicted merchantable volume with greater accuracy (higher R^2) than did Omerod's model (Model 2) over all species (Table 6). However, Omerod's model was more accurate in estimation of merchantable height, and was generally equal to Kozak's model in prediction of the square of minimum diameter (i.b.) over DBH. All regressions yielded R^2 values of greater than 90 percent.

The prediction of total volume using Kozak's model ranged from an R^2 value of .96646 and a standard error of .06526 for balsam poplar, to an R^2 value of .98643 and a standard error of .02704 for balsam fir. For Omerod's model, the lowest R^2 value was .96455 for balsam poplar, with a standard error of .06434; the highest was .98595 for balsam fir with a standard error of .02751. Both models overestimated total tree volume in large trees of white and black spruce.

Table 6. Results of regression of taper models by species.

Species group	MODEL 6						MODEL 7					
	d^2/DBH^2		Merchantable heights		Merchantable volume		log d^2/DBH^2		Merchantable heights		Merchantable volume	
	R^2	Se	R^2	Se	R^2	Se	R^2	Se	R^2	Se	R^2	Se
White spruce	.96393	0.05347	.96670	1.11969	.97780	0.08282	.97039	0.14745	.96776	1.10176	.97693	0.08442
Black spruce	.97314	0.06842	.92972	0.90908	.97247	0.01874	.95492	0.11467	.93011	0.90655	.96839	0.02008
Balsam fir+	.98220	0.04737	.96743	0.81452	.98714	0.02457	.98359	0.08845	.96655	0.82542	.98665	0.02503
Pine	.96185	0.06745	.95032	1.14467	.97719	0.04488	.96481	0.13362	.95190	1.12634	.97629	0.04576
Aspen	.96684	0.06018	.95042	1.19843	.97491	0.06711	.96243	0.15104	.95186	1.18093	.97432	0.06789
Balsam poplar++	.95533	0.0550	.93708	1.22401	.96462	0.06395	.93756	.21126	.94006	1.19469	.96222	0.06608

MODEL 6 Kozak's Taper Model (1969).

MODEL 7 Omerod's Taper Model (1973).

\+ VSR 4 only
++ VSRs 2,4 and 8 only

NOTE: The Se reported is the standard error for the merchantable volume.

4.4 Discussion

4.4.1 Merchantable Ratio Models

All models predicted the merchantable ratio with R^2 values of over 85 percent. Honer's two models which include merchantable height as a predictor (Models 1 and 4), gave better results than models without this value. However, because merchantable height is difficult to measure in sampling (Husch *et al.*, 1972), these models are not practical unless an improved means of estimating merchantable height is assumed.

The AFS model (Model 5) generally yielded high R^2 values and has the added advantages that:

1. Merchantable height is not required for estimation.
2. Changes in stump height are reflected by a change in the predicted merchantable ratio, even when the minimum top diameter is zero.

The disadvantage to this model was that total volume is generally overestimated (predicted merchantable ratio greater than one). The reason for this overestimation could be that Model 5 is based on a paraboloid shape for tree volume, whereas the original calculation of total volume from the sample volume employs a cone formula for the top section (See Section 2.2.1). The volume of the top section could be overestimated with this model.

Model 3 yielded R^2 values similar to Model 5. The model, generally, underestimated total volume and did not

respond to changing stump heights when the minimum top diameter was set to zero. The need for a model that predicts a different merchantable ratio for differing stump heights with a top diameter of zero, may not now be necessary, although in the future, as utilization standards change, this feature may be desirable.

Model 2 gave results similar to Model 3, though stump height was not included as a variable in the model. Any change in stump height then would require the model to be fit for the new data.

4.4.2 Taper Models

The R^2 values for all regressions were over 90 percent for both models and all species. The results indicate, then, that both of the models are accurate. The reason for these high R^2 values may be that the variability of the merchantable volume was limited; no stump heights were varied, and only four different minimum top diameters were represented. The original testing of Model 6 by Kozak and others (1969) showed that the model accounted for 95 percent of the variation of the squared diameter ratio. In testing Model 7, Omerod (1973) suggested that the use of a segmented model yielded better results than this simple model. Both Cao and others (1980) and Martin (1981) found that these two models were adequate, but not as accurate as more complex equations. For other estimates, such as the merchantable volume of small log pieces, or the diameter below stump

height, these models have been found to be biased (Demaerschalk and Kozak, 1977). The two models are accurate, then, in estimating the merchantable volume, merchantable height, and the squared diameter ratio as defined for this study. For radically different utilization specifications, or for small log portions, some bias may result, although further analysis is needed.

4.4.3 Comparison of the Two Methods

A comparison of the two methods, merchantable ratio prediction and integration of taper models, indicates that taper models have the capacity for greater accuracy than merchantable ratio models. In terms of R^2 values, Hypothesis 7 can be rejected, and the conclusion that taper models are more accurate should be made.

Taper functions can be used to replace a volume-based system; total and merchantable volume functions can be replaced by a single function describing stem taper. Even simple models, such as those tested in this project, can be more accurate than merchantable ratio models for predicting the merchantable volume. The taper functions are also accurate in predicting total volume.

More complex taper functions will possibly be needed as utilization standards change and as the need for precise estimates of diameter, merchantable height, or merchantable volume rises (Bruce *et al.*, 1968). Simpler functions have been shown to be biased for the base and top portions of the

tree stem (Demaerschalk and Kozak, 1977). Equations such as Max and Burkhart's (1976) segmented polynomial function or Omerod's function for a hyperboloid form (1981) should be tested for prediction of the present as well as possible future merchantable volume inventory needs. The problem with these more complex functions is that the calculations become unwieldy. Hilt (1980) developed a computer program for fitting the taper function he developed; Bruce and others (1968) suggest using a merchantable ratio for practical use of the function.

If a system incorporating merchantable ratio functions is already established, these functions can be converted to taper functions. The conversion procedure as described by Clutter (1980) involves the algebraic reorganization of the combined merchantable ratio and total volume function so that the minimum top diameter becomes the dependent variable (taper function). Thus, instead of completely replacing the established volume-based system, the advantage of an accurate taper function can be added by rewriting the merchantable ratio model to a taper model. The accuracy of the resulting taper function must be tested.

Taper functions are often incompatible with existing total volume functions (Munro and Demaerschalk, 1974) and any inventory system which uses a total volume function may be costly to replace. Taper functions can be mathematically conditioned to be compatible with total volume functions (Demaerschalk, 1971 and 1972). However, merchantable ratio

functions are inherently more compatible as they are dependent on total volume functions for estimating merchantable volume. The adoption of a taper function conditioned to predict total volume equal to the existing equation may prove more accurate.

4.5 Conclusion

Simple taper functions can provide accurate results in predicting the merchantable volumes represented in this project. They also predict total volume accurately. However, if an existing system incorporates a total volume function with a merchantable ratio model, the continued use of merchantable ratio models is more practical and estimates are quite accurate.

For future inventory analysis systems, the following options are available:

1. A taper-based system could be adopted for predicting total and merchantable volume, as well as merchantable height and minimum top diameter.
2. Existing merchantable ratio models could be converted to taper models. The resulting taper function, though, may not be as accurate as other taper models available.
3. The use of taper functions, conditioned to predict total volume equal to the existing total volume function may be the more accurate and practical route.

Overall, merchantable ratio functions and simple taper

functions are accurate for prediction of the present needs of merchantable volume estimation. A taper model is advantageous, but may not be feasible for use with an existing inventory system. Further testing of both methods to determine limitations is required.

5. Defect Estimation

5.1 Introduction

Internal defect is the amount of missing or crumbling wood. Each type of wood product has associated losses because of internal defect. Defect volumes between trees vary greatly depending on the disease susceptibility of the tree, the availability of pathogens, and various site characteristics. For this reason, estimation of defect is difficult; resulting estimates are often statistically poor.

The aim in estimation is to obtain the best estimate of defect by maximizing the reduction in the variance of the estimate, while minimizing the number of discrete and continuous predictors employed. A constraint on these predictors is that they must be quickly and easily measured on standing trees. Species, site indicators, and cull suspect indicators are examples of discrete variables previously used (Smith, 1973). These variables can be represented either through preliminary segregation of data or by indicator variables in a regression model. Continuous variables such as DBH, age, and number of conks can be directly used as independent variables in a regression model (Aho, 1974); they may also be translated to discrete units by dividing the range of the variable into classes.

For the AFS tree section data, defect volumes for sawlog and pulp product types were calculated (See Section

2.2.3). VSRs, species, and cull suspect classes are the discrete variables which can be used as predictors of defect. To best use these variables to reduce the variance of defect, statistically significant differences must be determined. First, differences in defect volume between species and between VSRs must be defined.

Hypothesis 8
There is no significant difference in percent defect (pulp or saw) between species.

Hypothesis 9
There is no significant difference in percent defect (pulp or saw) between VSRs.

Significantly different groups should be separated before estimating defect values. They may alternatively be represented as indicator variables in a regression model.

The following four defect indicator classes (cull suspect classes) are presently used by the AFS:

1. Nonsuspect
2. Scars and Others
3. Old Broken Top
4. Conk and Punk Knot.

The importance of these classes as indicators of internal defect was of interest.

Hypothesis 10
There is no significant difference in percent defect (pulp or saw) between cull suspect classes.

Again, significantly different cull classes can be represented as indicator variables in a regression model. The expected result is that the 'nonsuspect' class would

indicate less defect than the other classes.

The continuous variables represented in this study were age and DBH. The relationship between age and defect, and DBH and defect was determined by testing the following hypotheses:

<u>Hypothesis 11</u>
There is no significant relationship between age and percent defect(pulp/sawlog).

<u>Hypothesis 12</u>
There is no significant relationship between DBH and percent defect(pulp/sawlog).

If DBH or age is proven significant in estimating defect, data can be separated into classes, and an average defect percent calculated, or these variables can be represented directly as independent variables for regression estimation.

Once the significant discrete and continuous predictors are found, a regression model to incorporate all of the pertinent predictors can be developed.

%defect = f(DBH,age,cull indicators,. . .)

If all significant discrete variables are represented as indicator variables in the regression model, the model could become large. Hence, some of the discrete variables should be used to categorize data before regression analysis is attempted. Even though all significantly different variables are represented either in the regression model or in the segregation of data, the resulting regression model may be statistically insignificant.

Hypothesis 13
A regression model to estimate percent defect will not be significant.

Percent defect is the dependent variable in all tests rather than actual defect volume. By using percent defect, the variance in defect volumes contributed by differences in the total tree volumes is controlled.

5.2 Methods

Hypotheses 8 through 10 were tested using subprogram ANOVA of the SPSS statistical package, with an alpha of .05. Differences between pairs of group means were assessed using Scheffe's method for multiple comparisons. ANOVA were completed for the following:

1. Percent defect with species, by VSR (Hypothesis 8).
2. Percent defect with VSR, by species (Hypothesis 9).
3. Percent defect with cull class, by VSR species, and by VSR/species group (Hypothesis 10).

Two way analysis of variance to simultaneously test Hypotheses 8 and 9 was not attempted, because of the limitations of the SPSS version used; paired contrasts could not be done with two-way analysis of variance (Nie *et al.*, 1975). To replace this two-way analysis of variance, data were separated by species, when testing for VSR differences, and by VSR, when testing for species differences. Similarly, data were separated by species, by VSR, and by VSR/species groups in testing Hypothesis 10.

Regression of percent defect with age and DBH, separately, was employed to determine if these continuous variables significantly improve the estimate of defect percent (Hypotheses 11 and 12). An alpha level of .05 was used to determine whether the resulting regression was significant. Data were separated by VSR and species.

The results of all tests were then interpreted and a regression model was developed. The regression model was tested (Hypothesis 13) using multiple linear regression analysis, with a significance level of .05.

5.3 Results

5.3.1 Species Differences

Differences in percent pulp defect between species were significant in all but VSR 3 (Table 7). Aspen differed in percent pulp defect from all other species in VSRs 2 and 4. In VSR 8, aspen differed from black spruce and pine. No other species pairs were significantly different.

For all VSRs tested, differences in percent saw defect between species, as a group, were significant. Defect in aspen differed from all species in VSRs 2 and 4, and from all species except balsam poplar in VSR 8. Balsam poplar defect was different from pine in VSRs 2, 4, and 8, and from black spruce in VSRs 2 and 8.

Table 7. Differences in percent defect(pulp/saw) between species by VSR.

VSR	PULP DEFECT All Species F statistic	PULP DEFECT Significant differences between pairs of species	SAW DEFECT All Species F statistic	SAW DEFECT Significant differences between pairs of species
VSR 3	0.479	No pairs significantly different	3.803*	Black spruce and Pine different
VSR 2	35.833*	Aspen differs from Pine, Black spruce, White spruce and Balsam poplar	43.765*	Aspen differs from Pine, Black spruce, White spruce, and Balsam poplar; Balsam poplar also different from Black spruce and Pine
VSR 4	41.417*	Aspen differs from White spruce, Black spruce, Balsam fir, Pine, and Balsam poplar	70.956*	Aspen differs from White spruce, Black spruce, Balsam fir, Pine, and Balsam poplar; Balsam poplar also differs from Pine
VSR 8	8.085*	Aspen differs from Black spruce, and Pine	18.263*	Aspen differs from White spruce, Black spruce, and Pine;Balsam poplar different from White spruce, Black spruce, and Pine

* Significant at the .05 level

In VSR 8 (Lac La Biche-Athabasca region), balsam poplar differed in percent saw defect from white spruce. In VSR 3 (Rocky, high elevation), black spruce and pine defect percents were different.

5.3.2 VSR Differences

Differences in percent pulp defect between VSRs as a group were significant for two of five species tested (Table 8). VSR 4 differed from other regions for aspen. The VSRs, as a group differed in pulp defect for balsam poplar, although the difference is too small for any significant differences between individual regions.

In three of five species, differences in percent saw defect between VSRs were significant. For defect in black spruce, VSR 3 (Rocky, high elevation) differed from other VSRs. Pine in Rocky, low elevation (VSR 2) differed from pine in Lac La Biche-Athabasca region (VSR 8). As with pulp defect, VSR 4 differed in saw defect for aspen from other VSRs.

5.3.3 Defect Indicator Class Differences

Cull class differences by VSR for pulp defect (Table 9) were significant in all VSRs tested. Class 4 differed from other classes in VSRs 2, 4 and 8, and class 1 differed from 2 in VSRs 3 and 8. For saw defect, differences were noted between cull class 4 and other classes in VSRs 2 , 4 and 8.

Table 8. Differences in percent defect(pulp/saw) between VSRs by species.

Species	PULP DEFECT All VSRs F statistic	PULP DEFECT Significant differences between VSR pairs	SAW DEFECT All VSRs F statistic	SAW DEFECT Significant differences between VSR pairs
White spruce	0.959	No pairs significantly different	0.143	No pairs significantly different
Black spruce	0.468	No pairs significantly different	5.179*	VSR 3 different from VSRs 2, 4, and 8
Pine	1.596	No pairs significantly different	3.276*	VSR 2 differs from VSR 8
Aspen	35.234*	VSR 4 different from VSRs 2, 3 and 8	47.653*	VSR 4 different than VSRs 2, 3 and 8
Balsam poplar	3.074*	No pairs significantly different	1.670	No pairs significantly different

* Significant at the .05 level

Table 9. Differences in percent defect(pulp/saw) between cull classes by VSR group.

VSR	PULP DEFECT All Classes F statistic	PULP DEFECT Significant differences between cull class pairs	SAW DEFECT All Classes F statistic	SAW DEFECT Significant differences between cull class pairs
VSR 3	3.335*	Classes 1 and 2 different.	2.214	No pairs significantly different.
VSR 2	144.861*	Cull class 4 differs from classes 1, 2 and 3.	128.080*	Cull class 4 differs from classes 1, 2 and 3; 1 and 2 different.
VSR 4	192.328*	Cull class 4 differs from classes 1, 2 and 3	321.888*	Cull class 4 differs from classes 1, 2 and 3;class 1 differs from 2 and 3.
VSR 8	117.811*	Cull class 4 differs from classes 1, 2 and 3;class 1 differs from 2 and 3.	222.098*	All pairs different.

* Significant at the .05 level

Classes 1 and 2 were also different. In VSR 8, all pairs of classes were different in saw defect.

Table 10 shows cull class differences in percent pulp/saw defect by species. For pulp defect, no cull class differences were significant for black spruce; all pairs were different for white spruce. For pine and aspen, 'conk and punk' (class 4) was different in defect from other classes. Classes 1 and 2 were also different for aspen. For balsam poplar, cull class 3 was different from cull classes 1 and 2. For saw defect, cull class 4 differed from other classes for white spruce, balsam poplar, pine and aspen. Classes 1 and 2 varied in percent saw defect for all species except balsam poplar. For white spruce and balsam poplar, classes 2 and 3 were significantly different.

Table 11 is a summary of ANOVA tests for differences in pulp defect between cull classes by VSR/species group. In 11 of 20 VSR/species groups, cull class differences were significant. Generally, in aspen, 'conk and punk' (class 4) differed from 'nonsuspect' (class 1) and 'scars and others' (class 2). For VSR 2/black spruce, and VSR 8/aspen, classes 1 and 2 were different. Cull class 4 differed from class 1 in VSR 2/balsam poplar. For VSR 4/white spruce, class 4 differed from other classes. 'Scars and others'(class 2) was different from other classes for VSR 8/white spruce. 'Conk and punk knot' differed from other classes for VSR 8/pine. Class 3 was different from classes 1 and 2 for VSR 8/balsam poplar.

Table 10. Differences in percent defect(pulp/saw) between cull classes by species group.

Species	PULP DEFECT All Classes F statistic	PULP DEFECT Significant differences between cull class pairs	SAW DEFECT All Classes F statistic	SAW DEFECT Significant differences between cull class pairs
White spruce	28.534*	All pairs except 1 and 3 different.	39.753*	Cull class 4 differs 1, 2 and 3; class 2 differs from 1 and 3.
Black spruce	2.101	No pairs significantly different.	8.237*	Classes 1 and 2 different.
Pine	20.415*	Cull class 4 differs from classes 1, 2 and 3; 1 and 2 different.	17.768*	Cull class 4 differs from classes 1, 2 and 3; 1 and 2 different.
Aspen	165.413*	Cull class 4 differs from classes 1, 2 and 3; 1 and 2 different.	256.069*	Cull class 4 differs from 1, 2 and 3; 1 and 2 different.
Balsam poplar+	9.489*	Cull class 3 different from 1 and 2.	9.335*	Cull class 1 differs from classes 3 and 4; 2 and 3 different.

* Significant at the .05 level
\+ VSRs 2, 4 and 8 only

Table 11. Cull class differences in percent pulp defect by VSR/species group.

VSR/Species group		All Classes F statistic	Significant differences between cull class pairs
VSR 3	White spruce	1.434	No pairs significantly different
	Black spruce	0.170	No pairs significantly different
	Pine	2.858	No pairs significantly different
	Aspen	5.844*	Cull class 1 differs from 2**
VSR 2	White spruce	0.686	No pairs significantly different
	Black spruce	7.683*	Cull classes 1 and 2 different
	Pine	1.154	No pairs significantly different
	Aspen	44.429*	Cull class 4 differs from 1 and 2
	Balsam poplar	4.295*	Cull class 4** differs from cull class 1
VSR 4	White spruce	17.092*	Cull class 4** differs from cull classes 1, 2 and 3**
	Black spruce	0.128	No pairs significantly different
	Balsam fir	5.102*	Only 2 classes (1 and 2)
	Pine	0.305	No pairs significantly different
	Aspen	33.776*	Cull class 4 differs from cull classes 1 and 2
	Balsam poplar	3.107	No pairs significantly different
VSR 8	White spruce	18.221*	Cull class 2 differs from cull classes 1 and 3
	Black spruce	1.882	No pairs significantly different
	Pine	39.328*	Cull class 4 differs from cull classes 1, 2 and 3
	Aspen	71.221*	Cull class 4 differs from cull classes 1 and 2; 1 and 2 different
	Balsam poplar	5.911*	Cull class 3 differs from cull classes 1 and 2

* Significant at the .05 level
** Fewer than 5 samples.

ANOVA results for cull class differences in percent saw defect by VSR/species group are listed in Table 12. Differences were significant in 13 VSR/species groups. No differences were significant for all VSR 3/species groups. For aspen in the remaining VSRs, 'conk and punk knot' (class 4) differed from other classes. Generally, for white and black spruce, classes 1 and 2 were different. Classes 4 and 1 were different from other classes for VSR 8/ pine. In VSR 4, class 1 and 3 were different for balsam poplar, however, few observations were obtained for class 3, 'old broken top'.

5.3.4 Relationship of Age and Percent Defect

For 13 of 20 VSR/species groups tested, the relationship between percent pulp defect and age (Table 13) was significant for an alpha of .05. The range of R^2 values for significant regressions was .0095 to .2960; only three R^2 values were above .15. The higher R^2 values resulted with aspen. For black spruce, the regression was not significant in any VSR tested. In three VSRs, the relationship was so insignificant that no regression line could be calculated at the default tolerance level for SPSS.

Table 12. Cull class differences in percent saw defect by VSR/species group.

VSR/Species group	All Classes F statistic	Significant differences between cull class pairs
VSR 3 White spruce	3.014	No pairs significantly different
Black spruce	0.412	No pairs significantly different
Pine	2.692	No pairs significantly different
Aspen	1.251	No pairs significantly different
VSR 2 White spruce	7.867*	Cull class 1 differs from 2 and 3**
Black spruce	11.804*	Cull classes 1 and 2 different
Pine	3.866*	No pairs significantly different
Aspen	46.025*	Cull class 4 differs from 1 and 2
Balsam poplar	1.440	No pairs significantly different
VSR 4 White spruce	22.927*	Cull class 4** differs from cull classes 1, 2 and 3**;1 and 2 different
Black spruce	2.662	No pairs significantly different
Balsam fir	6.522*	Only 2 classes(1 and 2)
Pine	0.486	No pairs significantly different
Aspen	63.007*	Cull class 4 differs from cull classes 1, 2, and 3
Balsam poplar	6.528*	Cull classes 1 and 3** different
VSR 8 White spruce	24.658*	Cull class 2 differs from cull classes 1 and 3
Black spruce	7.136*	Cull classes 1 and 2 different
Pine	36.217*	Cull class 4 differs from cull classes 1, 2 and 3;1 different from 2 and 3
Aspen	114.387*	Cull class 4 differs from cull classes 1 and 2; 1 and 2 different
Balsam poplar	5.304*	Cull class 4 differs from cull class 1

* Significant at the .05 level
** Fewer than 5 samples.

Table 13. Regression results for percent defect(pulp/saw) with age.

VSR/Species group		PULP DEFECT F statistic	PULP DEFECT R^2	SAW DEFECT F statistic	SAW DEFECT R^2
VSR 3	White spruce	5.5597*	.0296	.5635	.0031
	Black spruce	NA		NA	
	Pine	43.4205*	.1109	42.6946*	.1093
	Aspen	5.8373*	.1585	.0296	.0010
VSR 2	White spruce	4.5305*	.0421	19.6099*	.1600
	Black spruce	NA		.3708	.0014
	Pine	.6204	.0013	.0642	.0001
	Aspen	10.6760*	.1040	8.8242*	.0875
	Balsam poplar	.4423	.0140	.0407	.0013
VSR 4	White spruce	6.6709*	.0253	18.3108*	.0665
	Black spruce	NA		NA	
	Balsam fir	1.3565	.0221	2.4743	.0396
	Pine	7.9538*	.0255	11.6954*	.0370
	Aspen	41.1995*	.2960	43.0536*	.3052
	Balsam poplar	5.8806*	.2570	3.2272	.1596
VSR 8	White spruce	4.1304*	.0095	7.2075*	.0165
	Black spruce	.7196	.0026	.8248	.0030
	Pine	17.0757*	.0393	19.4529*	.0446
	Aspen	58.4799*	.1270	58.3676*	.1268
	Balsam poplar	3.7664	.0700	4.7547*	.0868

* Significant at the .05 level

NA Because the defect values were very small or zero, a regression line could not be calculated using the default tolerance levels of the SPSS regression package.

Regressions of percent saw defect with age showed that in 12 of 20 VSR/species groups, the relationship was significant. Aspen, again, yielded some of the highest R^2 values with .3052 for VSR 4. The range of R^2 values for significant regressions was 0.0165 to .3052; only three of the R^2 values were above .15.

5.3.5 Relationship of DBH and Percent Defect

Table 14 is a list of the regression results for DBH and percent pulp and saw defect.

For 13 of 20 VSR/species groups, the regression with percent pulp defect was significant. As with age, the regression appears to be most significant for aspen. The range of R^2 values for significant regressions was .0145 to .2895, with only one of the R^2 values above .15.

For 11 of 20 VSR/species groups, the regression of DBH with percent saw defect is significant. The range of R^2 values for significant regressions was .0195 to .3415. The regression for aspen yielded a substantially higher R^2. Only two values were above .15.

Table 14. Regression results for percent defect(pulp/saw) with DBH.

VSR/Species group		PULP DEFECT F statistic	PULP DEFECT R^2	SAW DEFECT F statistic	SAW DEFECT R^2
VSR 3	White spruce	4.2944*	.0221	1.5718	.0082
	Black spruce	.0102	.0002	.0327	.0005
	Pine	5.1382*	.0145	11.0189*	.0305
	Aspen	.1333	.0034	.5924	.0015
VSR 2	White spruce	.5510	.0052	.0971	.0009
	Black spruce	3.0832	.0110	7.7827*	.0272
	Pine	.0223	.0001	.0436	.0001
	Aspen	8.3019*	.0571	5.7248*	.0401
	Balsam poplar	.6434	.0103	NA	
VSR 4	White spruce	17.0547*	.0598	25.9563*	.0883
	Black spruce	9.006*	.0521	11.4640*	.0653
	Balsam fir	2.4323	.0378	1.2716	.0201
	Pine	6.1929*	.0197	6.0518*	.0192
	Aspen	67.2162*	.2895	85.5699*	.3415
	Balsam poplar	2.5579*	.0963	2.4057	.0911
VSR 8	White spruce	12.4878*	.0264	10.3827*	.0220
	Black spruce	5.1378*	.0182	3.4936	.0125
	Pine	15.8412*	.0351	26.4257*	.0573
	Aspen	32.7188*	.0620	52.6243*	.0961
	Balsam poplar	5.3390*	.0665	9.0660*	.1078

* Significant at the .05 level

NA Regression statistics could not be calculated using the default tolerance level of SPSS.

5.3.6 Multiple Regression of Percent Defect

Using results from previous studies as a guide, and the results obtained in testing Hypotheses 8 through 12, the following regression model was developed for testing.

$$\% \text{ defect} = a + b\text{DBH} + c \text{ AGE} + d Z_1 + eZ_2 + fZ_3 \quad (7)$$

where DBH is the diameter(o.b.) at breast height(cm)
AGE is the age measured at stump height

Z_1 = 1, if 'nonsuspect', 0 else
Z_2 = 1, if 'scars and others', 0 else
Z_3 = 1, if 'old broken top', 0 else
all Zi are zero for 'conk and punk knot'.

The model is an adaptation of a model used by Aho (1974) and is similar to that used by Brown (1934). Coefficients were fitted using stepwise linear regression by species (Table 15). For pulp defect, the regression was significant for all species but black spruce. The regression for saw defect was significant for all species. The R^2 values for both pulp and sawlog defect were less than 40 percent, with higher values for aspen. In most cases, age entered first into the regression; the addition of DBH after age was usually insignificant and sometimes reduced the overall significance of the regression.

Table 15. Multiple regression results for predicting percent defect(pulp/saw).

Species	PULP DEFECT			SAW DEFECT		
	R^2	Se	F stat	R^2	Se	F stat
White spruce	.07300	.04986	15.22983*	.08355	.07571	17.63182**
Black spruce	.00836	.03626	1.26600	.04145	.05668	6.49551**
Balsam fir+	.15263	.08432	3.48243*	.16485	.13457	3.81621*
Pine	.04878	.04698	15.75293*	.05321	.07668	17.26568**
Aspen	.38018	.06107	76.42709**	.39497	.12252	81.34004**
Balsam poplar++	.11436	.04724	2.50510*	.17007	.09173	3.97546**

\+ only VSR 4 represented
++ only VSRs 2,4 and 8
* Significant at the .05 level
** Significant at the .01 level

5.4 Discussion

5.4.1 Species Differences

For both pulp and saw defect, Hypothesis 8 was rejected; species differences were significant. Pairwise comparisons of species revealed that aspen contributed most to the species differences; aspen differed from other species in both pulp and sawlog defect. Morawski (1967) reported that aspen differed in defect volume from other species in Ontario. Basham (1958) concluded that the susceptibility of aspen to decay hinders the use of the species. The results of this study support these earlier reports.

In addition to aspen, balsam poplar differed from other species for sawlog defect. This indicates that deciduous species should be estimated separately from coniferous species in defect estimation. As an isolated case, in the Rocky-Clearwater, high elevation, region, pine and black spruce differed in saw defect percentages. The reason for this difference is not obvious. Possibly, a pathogen may be present in this area which affects one of the species. However, many other factors including the hardiness of the genotypes, and the effects of the environment on the species may be contributing to this difference in defect.

5.4.2 VSR Differences

Differences in pulp defect between VSRs were generally not significant and so Hypothesis 9 could not be rejected. VSR 4 differed from other VSRs for aspen and hence this VSR should be segregated from other VSRs in estimating aspen defect.

For sawlog defect, only half of the six species tested were different in defect between VSRs, and so, again, Hypothesis 9 could not be rejected. For black spruce, VSR 3 should be estimated separately from other VSRs. VSRs 2 and 8 are different in pine defect; VSR 4 should be separated from other VSRs for aspen.

VSR differences are mostly insignificant except for a few isolated cases. The black spruce trees in the Rocky-Clearwater high elevation, were different from black spruce in other areas; many factors including environmental stress, a difference in genotype, or the presence of pathogens could be contributing to this difference. The difference in sawlog defect for pine in VSR 2 from VSR 8 is probably explained by the fact that two species, lodgepole pine (*Pinus contorta* var. *latifolia*) and jack pine (*Pinus banksiana*) were represented (Hosie, 1969). In VSR 2, lodgepole pine is most prevalent, whereas in VSR 8, jack pine is the prevailing pine species. Between these two areas (for example VSR 4), the species hybridize, so the difference in defect was not as notable between VSR 4 and VSR 2, or between VSR 4 and VSR 8. VSR 4 differs from all

other VSRs for aspen, indicating that the site and/or species differ in this region. Wall (1971) indicated that differences in defect between clones is apparent in aspen; Fowells (1965) cited both studies which supported and studies which refuted the idea that site is related to defect in aspen. For Alberta, this study indicates that differences in VSRs for aspen defect volume are significant for some regions.

Most forest management agencies separate lands into zones for estimating defect. The British Columbia Ministry of Forests separate the land base into ecological zones (Dobie and Kasper, 1974; British Columbia Forest Service, 1976). Manitoba stratifies by management unit (Manitoba Forest Inventory, 1981) and Saskatchewan expects to differentiate by forest administration units (Lindenas, 1981). This study indicates that separation by VSRs in Alberta does not significantly improve the estimate of defect percent.

5.4.3 Defect Indicator Class Differences

In all of the VSRs tested, for percent pulp defect, cull class differences were significant; 3 of 4 VSRs differed in percent saw defect. Hypothesis 10 was then rejected. Classes 1 and 4, and 1 and 2 were almost always different; for a few VSRs, 'old broken top' (class 3) was also different. By species, cull classes differed in pulp defect for five of six species and in sawlog defect for all

species. Over half of the VSR/species groups showed significant differences in values for pulp and saw defect between cull classes. Again, classes 1 and 4, and 1 and 2 were most commonly different.

In general, cull classes are significantly different by species, by VSR, and by VSR/species group. These differences are hard to quantify; a further complication is that stems often possess more than one indicator (Allemdag and Honer, 1972). The classes tested in this study may not be the best indicators of defect, although the use of 'conk', 'scars', and 'knots' as indicators is common (Bailey and Dobie, 1977; Aho, 1974). Other indicators of defect that have been used are 'rot diameter at one foot' (Brown, 1934), growth rate (Stayton *et al.*, 1970), and 'frequency of unsound knot' (Allemdag and Honer, 1972). However, the use of 'conk' for aspen, and 'scars and others' for balsam poplar have been found to be the most commonly recorded indicators of internal defect in Slave Lake, Alberta (Bailey and Dobie, 1977). The results of this study show that the AFS cull indicator classes significantly contribute to the estimation of defect.

5.4.4 Relationship of Age with Percent Defect

Age, as an independent variable, significantly reduced the variance of pulp and saw defect for over half of the VSR/species groups tested, however the associated R^2 values were very low. Hypothesis 11 was therefore rejected.

Although Morawski (1967) stated that cull was related to age for all tree species, this study indicated that for Alberta, age and defect are significantly related only for a few species, particularly aspen and pine, and these relationships are relatively weak. Bailey and Dobie (1977) found that age is significantly related to defect for aspen; age was not significantly related to defect for balsam poplar. Basham (1958) also concluded that defect increased with age in aspen. The R^2 values were higher for aspen, but the age is difficult to measure in this species; annual rings are often indescriminant (Maini and Coupland, 1964). Age as a predictor of defect is significant for some species, but may not be easily measured and resulting R^2 values are low.

5.4.5 Relationship of DBH with Percent Defect

Because age is difficult to measure, DBH is often substituted as a predictor (Morawski, 1967). For these data, similar results were obtained for the regression of DBH with defect as with age and defect, and hence Hypothesis 12 was also rejected. The range of R^2 values was again low, with aspen and pine yielding the highest values. The use of DBH, instead of age, is feasible though neither DBH nor age greatly reduces the variance of defect. DBH as a predictor of defect for aspen and pine appears to be more significant than in other species. The reduction in variance with other species is minimal.

5.4.6 Multiple Regression of Percent Defect

Multiple regression to estimate defect has been attempted by many authors (Aho, 1974; Aho and Simonski, 1975; Stayton *et al.*, 1970). The results obtained through multiple regression of the model which uses DBH, age and AFS cull indicator classes had a maximum R^2 value of less than 40 percent for pulp and saw. In the stepwise regression procedure, DBH was always entered after age. The later addition of DBH sometimes reduced the significance of the overall regression, and the variable DBH was not significant given the other variables were in the model. Other variables such as 'rot diameter at one foot above ground', successfully used by Brown (1934), might be included to improve the regression. Some preliminary stratification by region may have improved the regression estimate, although, differences in defect between VSRs were found to be significant only for a few VSR pairs.

5.5 Conclusions

Because the multiple regression model developed yields low R^2 values, the defect percentage estimates produced are not very accurate. For large scale inventories, on the average, the estimates may be adequate, but for small areas, and few species, they would not be accurate.

If the multiple regression model is to be used, the following breakdown to reduce variance is suggested, based

on the regression, and analysis of variance tests.

1. Aspen must be separated from other species for both pulp and sawlog defect estimates. VSR 4 should be separated from other VSRs for aspen.
2. Balsam poplar should be also be separated from other species, though one estimate can be used for all three VSRs tested.
3. For VSR 3, sawlog defect, pine and black spruce should be separated.
4. Cull classes can be employed to reduce defect variance. The 'old broken top' class rarely helped to reduce variance; another indicator class may be more related to defect.
5. Classification by age or DBH class is suggested for some species, particularly aspen and pine.

The regression model for estimation of defect volumes using discrete and continuous predictors of defect is significant, but hardly accurate. Other indicators of defect for use in the regression may improve the estimate. Another method of estimating defect such as a mill study, or local cull study may be required for a more accurate estimate of defect volume.

6. Final Conclusions and Recommendations

Methods for estimating total, merchantable and defect volumes for four regions of Alberta were assessed. Although many methods have been developed for each type of volume, the methods tested were the most popular because of accuracy and useability.

For total volume estimation, standard volume functions, which use DBH and height as predictors, are more accurate than local volume functions (DBH only). Of the standard volume functions, the nonlinear models are the preferred models. Logarithmic transformations of these models to a linear form are also accurate, however transformed values are then minimized in the least squares procedure. Linear models, especially Spurr's constant or variable form-factor equations, are accurate, but the assumption of equal variance is not met. VSR differences appear to be more significant than species differences, once variation due to diameter and height is accounted for.

Merchantable volume, as specified in this project, is better predicted through the integration of taper models, than through the use of merchantable ratio models. Both models produce very adequate results. The choice of which of the two methods to implement depends on:

1. The present inventory system. If the system is rigidly based on a total volume function, taper models may be conditioned to be compatible, although merchantable ratio models may be more practical for this situation.

2. The type and precision of estimates which will be required for future inventories. If prediction of merchantable height, merchantable volume, and minimum top diameter is required, for varied portions of the stem, taper models are more suited.

The choice of methods for merchantable volume estimation, as defined in this study, remains a decision of what method is most practical for use.

Defect volumes must be estimated separately by product type. The wide variability of defect makes the development of an adequate regression model difficult, and the regression model developed was of marginal value. Other variables, more correlated with defect, may be found, or another type of defect estimation such as a mill study could be employed. The regression model developed can yield a general estimate of defect percentages for use in a large scale inventory. To obtain the best estimate of defect using the regression method and present variables, data should be separated by AFS cull indicator classes. Age or DBH significantly reduce the variability of some species, particularly aspen. Aspen should be estimated separately from other species, as should balsam poplar. Some regions can be combined, for example, one estimate of percent defect (pulp or saw) for balsam poplar can be used in the three VSRs tested.

Other species and VSRs in Alberta must be assessed for each of the three types of volume analysis. A nonlinear

regression model for total volume prediction is most accurate if a time and cost efficient statistical package for nonlinear regression is available. Additional taper models should be examined for use in Alberta. For defect, the regression method for large scale inventories is promising, however, other variables for predicting this value are needed.

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APPENDIX I. Sample tally sheets showing parameters recorded in tree sectioning.

APPENDIX IA. Record sheet in use prior to 1977.

APPENDIX IB. Record sheet for 1977 through to 1982.

APPENDIX I A

Alberta Forest Service -- Inventory Survey Section

TREE SECTION TALLY SHEET

LS	Sec	Twp	Rge	W Mer	Name	

Plot # or remarks

Dom	CoD	Int	Sup	Paul:	1.NS	2.S&O	3.OBT	4.C&PK	Vis defect%	B Ht age

(Species code: 1.Sw 2.Sb 3.Fb 4.P 5.A 6.Bw 7.Lt 8.Fd 9.Pb)
(Complete to col.14 before felling. Fell at 1.0' stump. Mark sections before cutting.)

← K E Y P U N C H   O N L Y →

Tree Number 1	Man. unit 6	Sp 10	DBH OB 12	Stump DIB 16	Height 20	Stump age 24
			.	.		

Log 1		Log 2		Log 3		Log 4		Log 5		Log 6		Log 7		Card # 77
L 28	D	L 35	D	L 42	D	L 49	D	L 56	D	L 63	D	L 70	D	
3.5	.	.	.	.	.	.	.	.	.	.	.	.	.	

(Card # = 0 up to 7 logs; above 7 logs complete cards 1 & 2.)
(KP: for cd.2, cols 1-10 must agree with cd.1; cols 12-24 may agree or may be blank.)

Log 8		Log 9		Log 10		Log 11		Log 12		Log 13		Log 14		Card # 77
L 28	D	L 35	D	L 42	D	L 49	D	L 56	D	L 63	D	L 70	D	
.	.	.	.	.	.	.	.	.	.	.	.	.	.	

STUMP	Stain D	Rot D	Remarks				
1	2	3	4	5	6	7	Log #
							Stain D
							Rot D
							Remarks
8	9	10	11	12	13	14	Log #
							Stain D
							Rot D
							Remarks

← Cull & defect desc. →

(Use reverse for diagrams and comment)	Transator #	LF	N	N

FMOPC 81-19
T/M F 2.34
1981 08 28
T/M F 3.9

A.F.S. TREE SECTIONING TALLY SHEET

NAME ______________________ DATE ____________

Mark Stump and Breast Height and Fill In All Essential Boxes up to and Including Crown Class Before Felling

Plot	Tree	Twp	Rge	M		M. Unit	SP	Dead (X)	Total # Sections
					1				
							20	22	23

DBH (OB)	At top of SEC	DECAY INC	TREE CATEGORY 1	2	3	4	5	Crown Class	Height	Imperial Units (X)	Internal Defects Imperial Converted to (X)
24		29	30					40	41	46	47

For Office Use Only

Large Scale Photo Area (Always Metric)

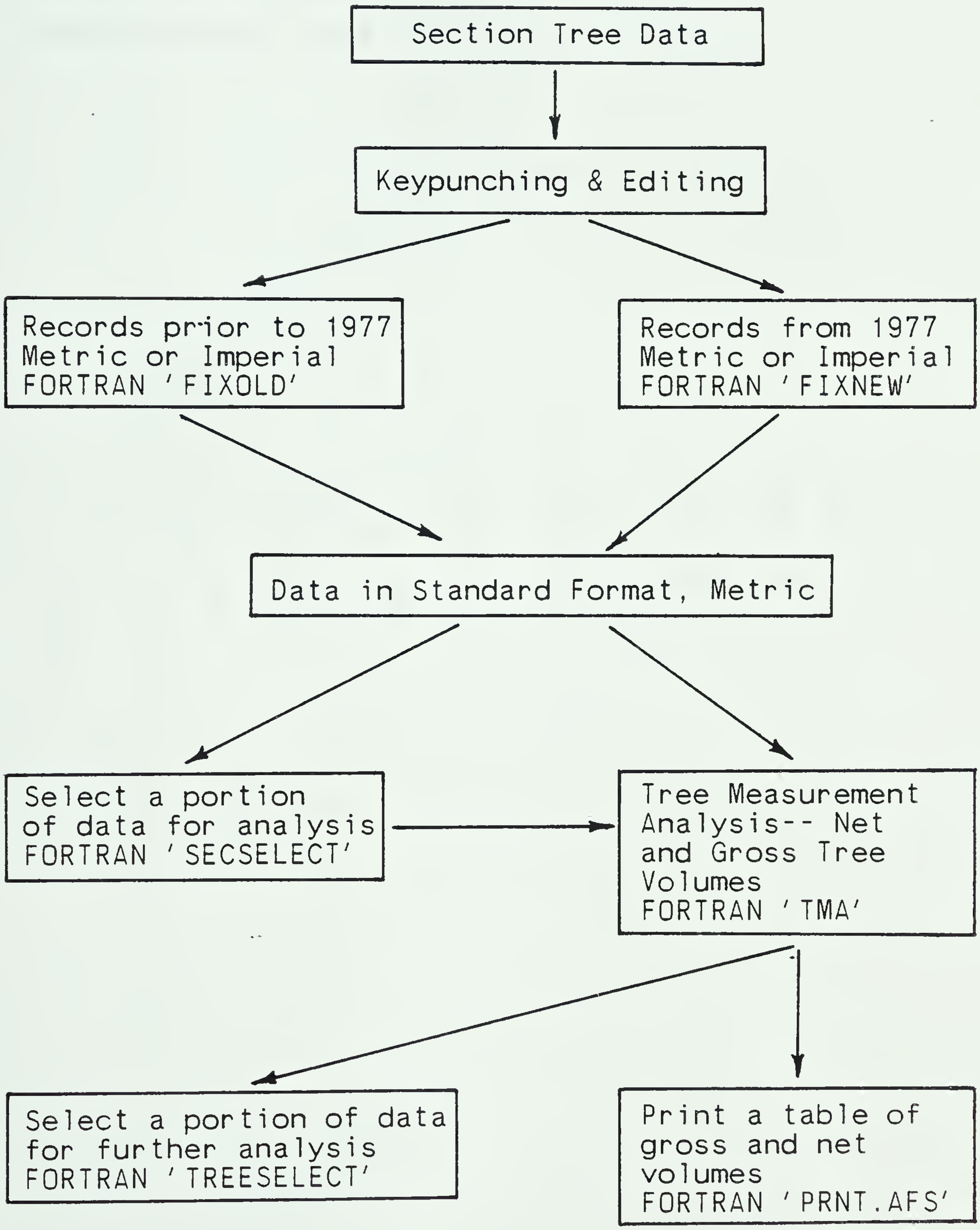
Operator ID	SP	CROWN C	CROWN Area	Height

Page	SEC NO.	LENGTH OF SECTION	TOP DIAMETER OF SECTION: Inside Bark	Outside Bark	Inside Bark	Outside Bark	AGE	EXTERNAL DEFECTS: Pulp	Saw	IMPERIAL UNITS ☐ (X) INTERNAL DEFECT: Pulp	Saw	
2	01											1
	02											2
	03											3
	04											4
	05											5
	06											6
	07											7
	08											8
	09											9
	10											10
	11											11
	12											12
	13											13
	14											14
	15											15
	16											16
	17											17
	18											18
	19											19
	20											20
	2	6	10	14	18	22	25		29	30	36	

APPENDIX II. Flowchart of Computer Programs.

APPENDIX II

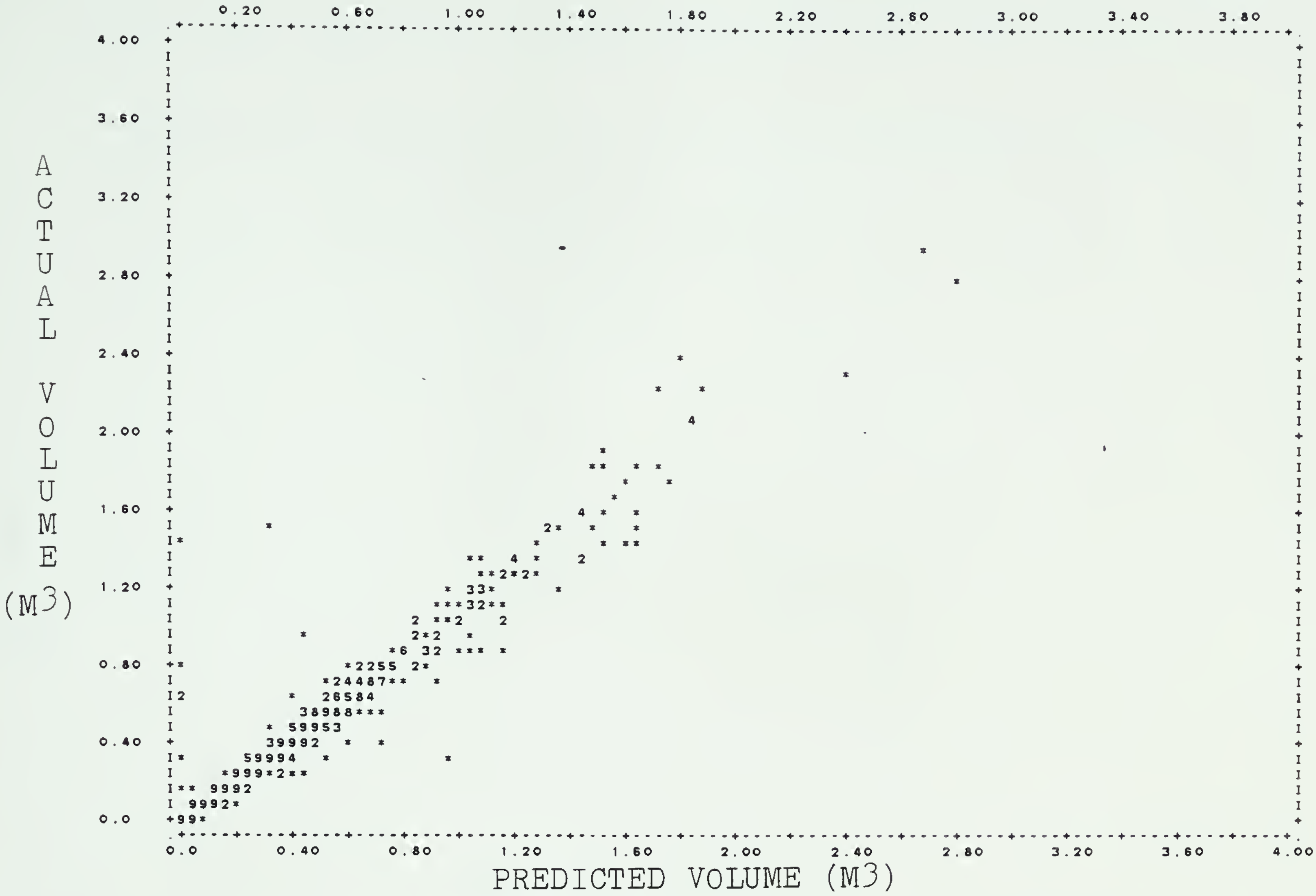
Flowchart of Computer Programs



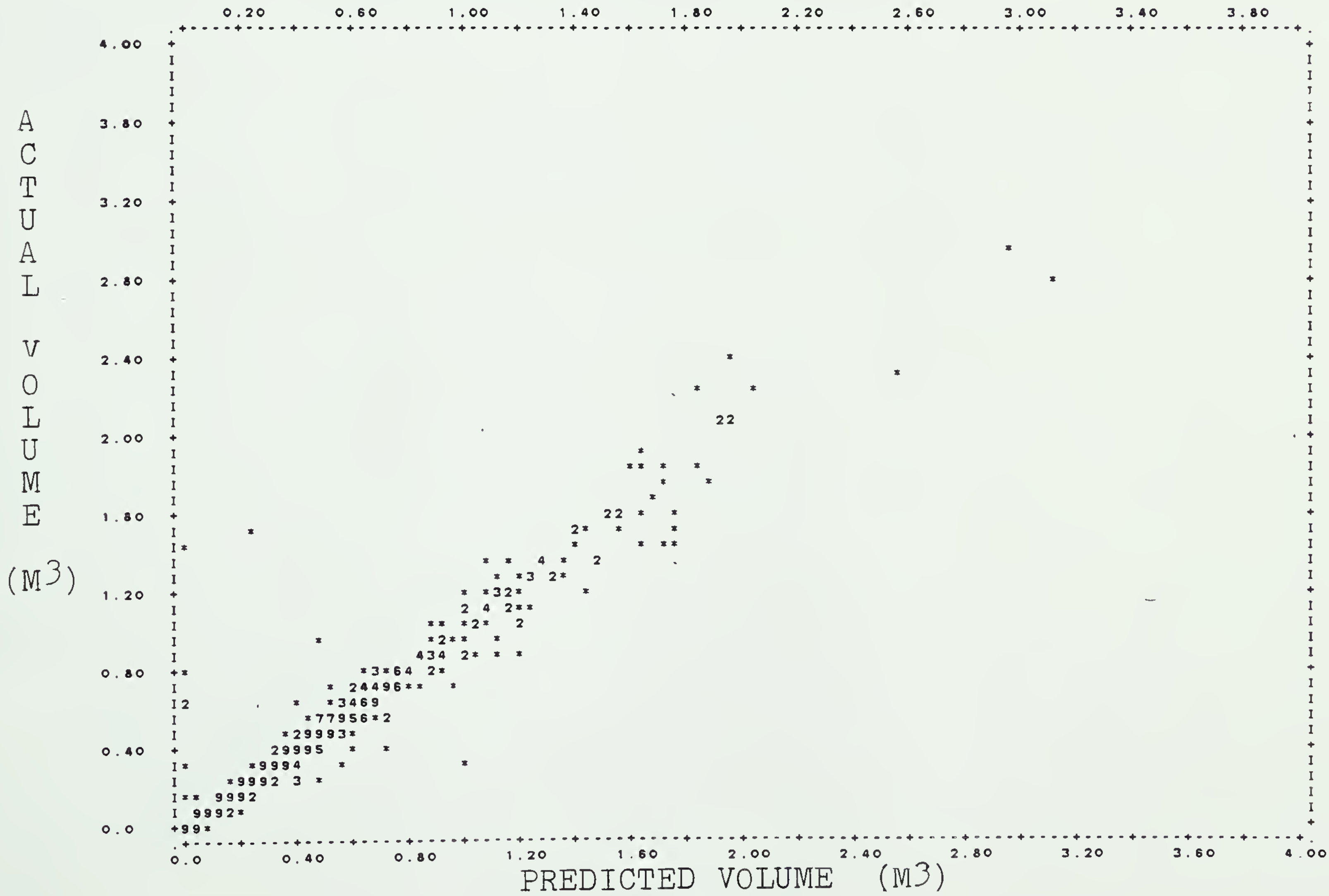
APPENDIX III. Graphical comparison of nonlinear and linearized versions of Models 3 and 7 for estimating total volume.

APPENDIX IIIA. Model 3.

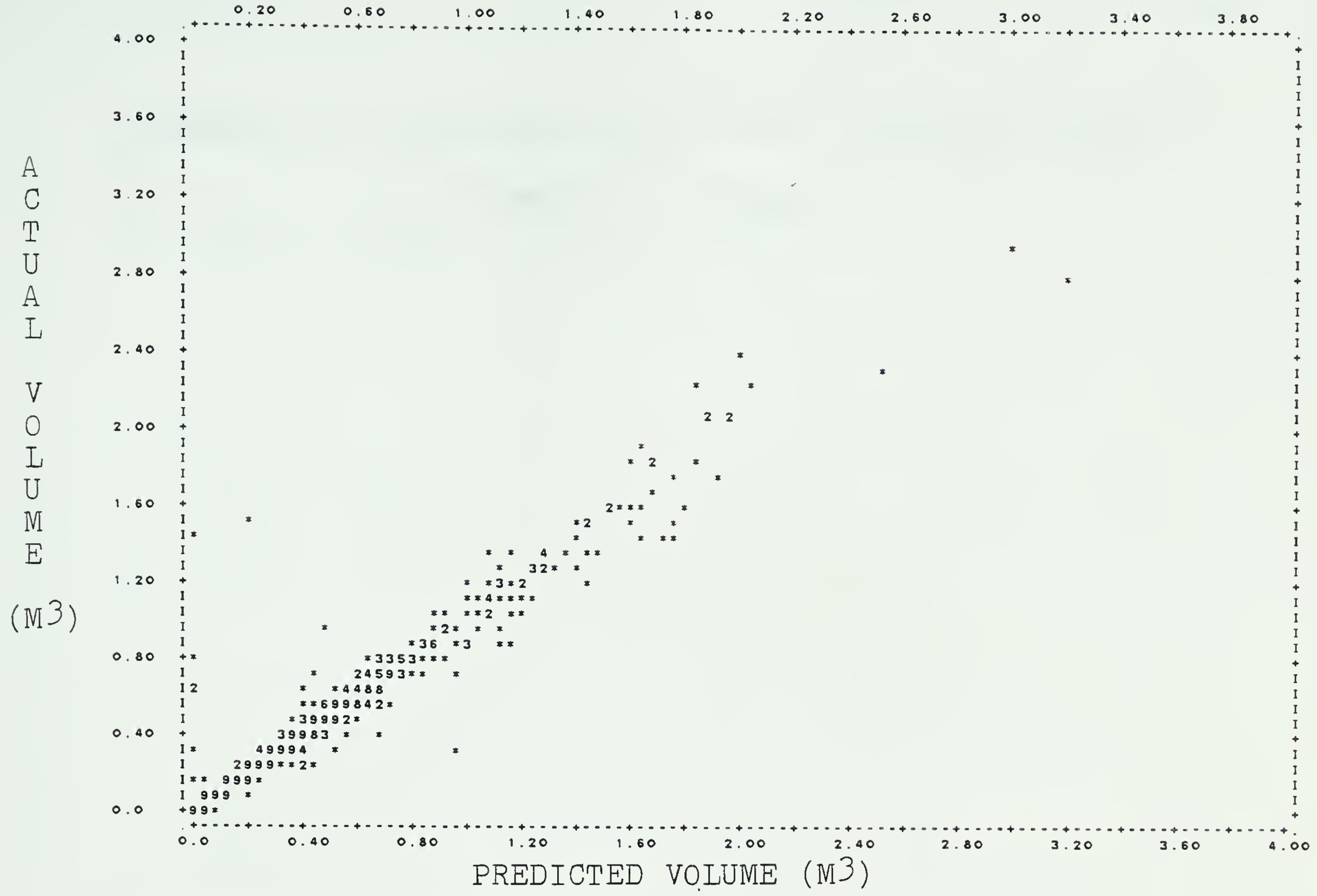
APPENDIX IIIB. Model 7.



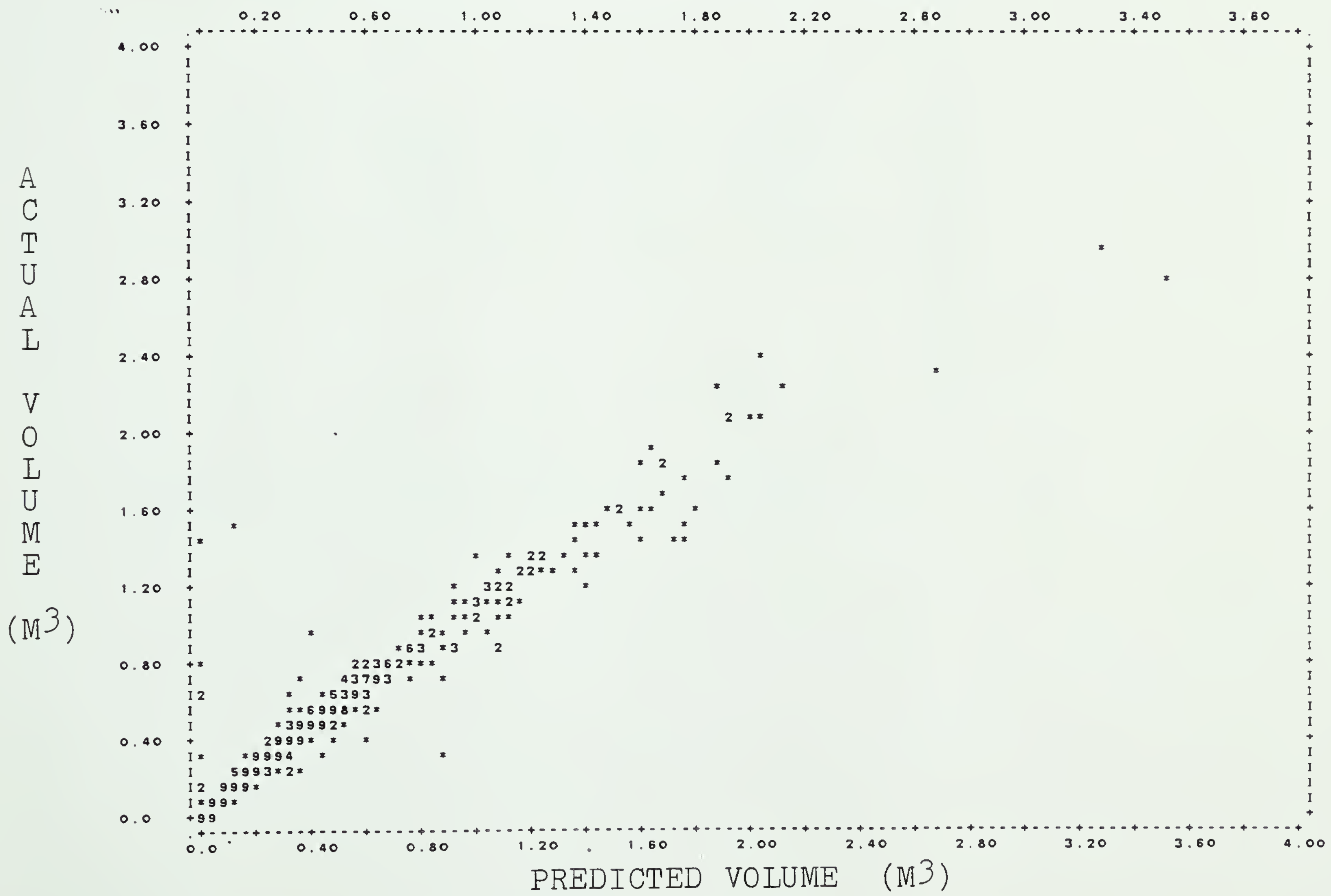
GRAPH 1: Actual volume vs predicted volume using the linear transformation of Model 3.



GRAPH 2: Actual volume vs predicted volume using the nonlinear version of Model 3.



GRAPH 3: Actual volume vs predicted volume using the linear transformation of Model 7.



GRAPH 4: Actual volume vs predicted volume using the nonlinear version of Model 7

APPENDIX IV. Selected statistics for individual volume estimation in Alberta.

Table IV.1. Regression coefficients for VSR/species groups using the logarithmic transformation of Schumacher's volume function.

VSR/Species group	a	b	c	R squared
VSR 3				
White spruce	.0000495	1.811218	1.042463	.99324
Black spruce	.0000457	1.898510	0.9665564	.98852
Pine	.0000318	1.904652	1.160143	.99386
Aspen	.0000350	1.963423	1.002920	.98812
VSR 2				
White spruce	.0000552	2.366416	0.3709238	.98130
Black spruce	.0000382	1.927188	0.9916466	.97602
Pine	.0000327	1.922063	1.112815	.97492
Aspen	.0000640	2.346836	0.3802759	.98478
Balsam poplar	.0000461	2.390473	0.3819264	.94342
VSR 4				
White spruce	.0000382	1.935935	1.006844	.99121
Black spruce	.0000358	2.025222	0.9240388	.99015
Balsam fir	.0000310	2.087444	0.9368331	.99395
Pine	.0000247	2.102790	1.010467	.99061
Aspen	.0000236	2.074807	1.024157	.99402
Balsam poplar	.0000265	1.934920	1.104489	.98937
VSR 8				
White spruce	.0000462	1.970372	0.9035523	.99356
Black spruce	.0000479	1.308748	1.559570	.95277
Pine	.0000508	1.795837	1.068126	.99041
Aspen	.0000372	1.854176	1.112407	.98973
Balsam poplar	.0000290	1.875014	1.119759	.98979

NOTE: All functions were developed using the logarithmic transformation of Schumacher's volume mode. The functions were then rewritten into the true form by taking the antilog of the coefficients.

MODEL: $V = a D^b H^c$

Table IV.2. Coefficients for merchantable volume functions by VSR/species group.

VSR/Species group	a	b	c	R squared	Se
VSR 3					
White spruce	.26980	.04531	.67113	.93067	.03296
Black spruce	.89537	-1.5510	1.6677	.86048	.04985
Pine	.048049	.96986	-.034409	.90708	.04529
Aspen	.39196	-.20341	.81932	.91741	.04377
VSR 2					
White spruce	.23864	.26884	.47240	.90312	.03745
Black spruce	.28242	.12733	.62086	.71865	.08901
Pine	.16006	.55509	.28500	.86925	.05325
Aspen	.37696	-.25625	.88699	.85686	.05215
Balsam poplar	.82947	-1.6176	1.7979	.86894	.04366
VSR 4					
White spruce	.10931	.56449	.32420	.90612	.03786
Black spruce	.026725	.90119	.093934	.84878	.06551
Balsam fir	.018774	.96167	.022058	.93988	.03590
Pine	.024309	1.07686	.049853	.89524	.04241
Aspen	.13587	.57353	.29360	.91335	.03670
Balsam poplar	.14138	.50339	.34869	.83508	.04835
VSR 8					
White spruce	.20736	.28397	.50337	.90730	.03914
Black spruce	.44731	-.31883	.89689	.81387	.07075
Pine	.48746	-.43510	.95791	.87856	.05287
Aspen	.27605	.17074	.55410	.91638	.04578
Balsam poplar	.27315	-.35506	1.0921	.89434	.04492

MODEL: $MR = a + b\,G + c\,G^2$

where $G = \left(1 - \frac{hs}{HT}\right)^2 - \left(\frac{DTOP}{DBH}\right)^4$

and a, b, and c are coefficients

Table IV.3i. Defect percentages. Pulp Classes. Nonsuspect. VSR 3.

	DIAMETER CLASSES(cm)												
Species	0.0 to 12.4	12.4 to 17.4	17.4 to 22.4	22.4 to 27.4	27.4 to 32.4	32.4 to 37.4	37.4 to 42.4	42.4 to 47.4	47.4 to 52.4	52.4 to 57.4	57.4 to 62.4	62.4 to 67.4	67.4+
White spruce													
Ave.%def	.17	.04	.09	.18	1.78	4.48	.77	-	8.13	0.0	-	-	-
Ave. DBH	10.10	14.36	20.19	24.67	29.77	34.51	39.45	-	50.05	54.05	-		
#Trees	19	28	40	32	26	14	10	0	2	2	0	0	0
Black spruce													
Ave.%def	.12	2.35	.70	0.0	0.0	-	-		-	0.0	-	-	
Ave. DBH	10.15	15.29	19.54	23.05	28.60	-	-		-	53.20	-	-	
#Trees	22	18	16	2	2	0	0	0	0	1	0	0	.0
Pine													
Ave.%def	0.0	0.0	.01	0.0	3.49	.03	0.0		-	0.0	-	-	
Ave. DBH	10.02	14.86	19.69	24.95	29.17	34.42	39.33	-	-	53.50	-	-	
#Trees	37	59	53	34	19	16	3	0	0	1	0	0	0
Aspen													
Ave.%def	.10	.22	.08	.27	-	-	-	-		-	-	-	
Ave. DBH	10.11	14.86	19.37	24.10	-	-	-	-		-	-	-	
#Trees	7	18	9	2	0	0	0	0	0	0	0	0	0

Table IV.3ii. Defect percentages. Pulp Classes. Nonsuspect. VSR 2.

Species	DIAMETER CLASSES(cm) 0.0 to 12.4	12.4 to 17.4	17.4 to 22.4	22.4 to 27.4	27.4 to 32.4	32.4 to 37.4	37.4 to 42.4	42.4 to 47.4	47.4 to 52.4	52.4 to 57.4	57.4 to 62.4	62.4 to 67.4	67.4+
White spruce													
Ave.%def	0.0	.44	0.0	0.0	.59	2.67	0.0	1.13	0.0	0.0	0.0	-	
Ave. DBH	10.16	14.62	19.82	25.78	29.78	34.14	39.00	43.32	51.00	54.80	59.38		
#Trees	10	21	11	10	12	11	3	4	2	1	4	0	0
Black spruce													
Ave.%def	.36	.21	.31	0.0	-	0.0	-		-	-	-	-	
Ave. DBH	9.92	14.58	18.83	23.43	-	35.10	-		-	-	-	-	
#Trees	98	88	24	7	0	1	0	0	0	0	0	0	0
Pine													
Ave.%def	0.0	.37	.07	.15	0.0	0.0	1.23	0.0	-	0.0	-	-	
Ave. DBH	10.23	15.51	20.00	24.69	29.76	35.11	39.27	44.82	-	52.60	-	-	
#Trees	25	58	81	72	23	16	7	4	0	1	0	0	0
Aspen													
Ave.%def	.61	0.0	3.64	.90	2.18	2.63	5.53	.08	-	-	-	-	
Ave. DBH	9.75	14.76	19.81	24.57	29.46	33.87	38.55	45.36		-	-	-	
#Trees	15	10	13	18	12	10	2	5	0	0	0	0	0
Balsam poplar													
Ave.%def	5.0	0.0	0.0	.31	.94	1.30	0.0	.36	.48	-	-	-	
Ave. DBH	8.50	14.23	20.60	24.15	30.09	35.24	39.10	43.97	47.80	-	-	-	
#Trees	2	3	3	11	8	5	3	3	1	0	0	0	0

Table IV.3iii. Defect percentages. Pulp Classes. Nonsuspect. VSR 4.

Species	0.0 to 12.4	12.4 to 17.4	17.4 to 22.4	22.4 to 27.4	27.4 to 32.4	32.4 to 37.4	37.4 to 42.4	42.4 to 47.4	47.4 to 52.4	52.4 to 57.4	57.4 to 62.4	62.4 to 67.4	67.4+
	DIAMETER CLASSES(cm)												
White spruce													
Ave.%def	0.0	0.0	.07	3.48	.30	.67	4.23	1.62	0.0	-	-	13.13	
Ave. DBH	9.91	15.03	19.97	24.38	29.76	34.33	39.51	44.25	49.08	-	-	66.30	
#Trees	15	27	48	54	37	25	17	4	4	0	0	1	0
Black spruce													
Ave.%def	0.0	.05	2.91	9.64	-	0.0	-		-	-	-	-	
Ave. DBH	10.46	14.40	18.97	24.47	-	35.10	-		-	-	-	-	
#Trees	33	66	23	9	0	1	0	0	0	0	0	0	0
Balsam fir													
Ave.%def	0.0	2.33	.64	.05	.42	0.0	-		-	-	-	-	
Ave. DBH	8.88	15.02	19.57	23.38	29.72	36.60	-	-	-	-	-	-	
#Trees	4	13	15	10	6	1	0	0	0	0	0	0	0
Pine													
Ave.%def	0.0	.28	.62	.87	3.19	0.0	0.0	0.0	-	-	-	-	
Ave. DBH	9.65	15.04	19.70	24.90	29.57	34.65	40.65	46.20	-	-	-	-	
#Trees	21	35	51	53	24	11	2	1	0	0	0	0	0
Aspen													
Ave.%def	1.95	.80	3.16	.50	.73	1.76	-	-	-	-	-	-	
Ave. DBH	10.76	15.05	20.15	24.58	28.68	32.90	-	-		-	-	-	
#Trees	5	16	19	9	4	2	0	0	0	0	0	0	0
Balsam poplar													
Ave.%def	0.0	0.0	0.0	3.86	0.0	.18	1.40	44.15	-	-	-	-	
Ave. DBH	9.70	15.00	20.20	24.15	28.12	33.82	40.10	45.20	-	-	-	-	
#Trees	1	2	2	2	5	4	2	1	0	0	0	0	0

Table IV.3iv. Defect percentages. Pulp Classes. Nonsuspect. VSR 8.

Species	DIAMETER CLASSES(cm) 0.0 to 12.4	12.4 to 17.4	17.4 to 22.4	22.4 to 27.4	27.4 to 32.4	32.4 to 37.4	37.4 to 42.4	42.4 to 47.4	47.4 to 52.4	52.4 to 57.4	57.4 to 62.4	62.4 to 67.4	67.4+
White spruce													
Ave.%def	0.0	.22	.55	.18	2.12	1.08	1.26	10.94	0.0	.07	-	17.53	
Ave. DBH	9.08	14.53	19.74	24.82	29.80	34.92	39.32	44.32	49.72	54.86	-	64.15	
#Trees	40	62	68	57	47	40	26	12	6	8	0	2	0
Black spruce													
Ave.%def	.06	0.0	2.98	5.25	0.0	-	-		-	-	-	-	
Ave. DBH	9.48	14.41	19.89	24.38	30.70	-	-		-	-	-	-	
#Trees	111	74	28	6	1	0	0	0	0	0	0	0	0
Pine													
Ave.%def	0.0	.08	0.0	0.0	2.45	10.61	1.04	-	-	-	-	-	
Ave. DBH	9.44	14.63	19.57	24.63	30.11	33.67	39.95	-	-	-	-	-	
#Trees	113	57	45	20	17	9	4	0	0	0	0	0	0
Aspen													
Ave.%def	.17	.14	1.62	.06	.89	.78	.40	7.92	0.0	-	-	-	
Ave. DBH	9.64	14.75	19.63	24.50	29.07	34.89	39.29	42.75	47.90	-	-	-	
#Trees	97	83	75	41	23	9	7	2	1	0	0	0	0
Balsam poplar													
Ave.%def	1.13	.03	1.23	2.74	4.12	1.71	0.0	3.11	-	-	-	-	
Ave. DBH	8.20	14.42	19.78	25.07	29.68	34.52	38.80	45.00	-	-	-	-	
#Trees	10	4	11	6	6	5	1	2	0	0	0	0	0

Table IV.4i. Defect percentages. Saw Class. Nonsuspect. VSR 3.

	DIAMETER CLASSES(cm)												
Species	0.0 to 17.8	17.8 to 22.8	22.8 to 27.8	27.8 to 32.8	32.8 to 37.8	37.8 to 42.8	42.8 to 47.8	47.8 to 52.8	52.8 to 57.8	57.8 to 62.8	62.8 to 67.8	67.8 to 72.8	72.8+
White spruce													
Ave.%def	2.55	.99	.60	2.44	5.42	3.06	-	12.17	0.0	-	-	-	
Ave. DBH	14.92	20.47	25.42	30.44	34.29	39.25	-	50.05	54.05	-	-		
#Trees	23	43	34	20	13	11	0	2	2	0	0	0	0
Black spruce													
Ave.%def	26.84	8.74	0.0	0.0	-	-	-		0.0	-	-	-	
Ave. DBH	15.67	19.86	23.50	28.60	-	-	-		53.20	-	-	-	
#Trees	17	16	1	2	0	0	0	0	1	0	0	0	0
Pine													
Ave.%def	.80	.18	0.0	9.60	0.0	0.0	-		0.0	-	-	-	
Ave. DBH	15.34	20.17	25.31	29.66	34.13	38.52	-	-	53.50	-	-	-	
#Trees	63	47	35	17	13	5	0	0	1	0	0	0	0
Aspen													
Ave.%def	9.83	.80	2.85	-	-	-	-	-		-	-	-	
Ave. DBH	15.95	19.58	24.10	-	-	-	-	-		-	-	-	
#Trees	11	8	2	0	0	0	0	0	0	0	0	0	0

Table IV.4ii. Defect percentages. Saw Class. Nonsuspect. VSR 2.

Species	DIAMETER CLASSES(cm) 0.0 to 17.8	17.8 to 22.8	22.8 to 27.8	27.8 to 32.8	32.8 to 37.8	37.8 to 42.8	42.8 to 47.8	47.8 to 52.8	52.8 to 57.8	57.8 to 62.8	62.8 to 67.8	67.8 to 72.8	72.8+
White spruce													
Ave.%def	4.77	0.0	0.0	2.06	5.17	0.0	2.33	0.0	0.0	0.0	-	-	
Ave. DBH	15.49	20.33	26.07	30.45	34.29	39.00	43.32	51.00	56.25	59.93	-		
#Trees	18	9	12	11	10	3	4	2	2	3	0	0	0
Black spruce													
Ave.%def	1.08	2.06	0.0	-	0.0	-	-		-	-	-	-	
Ave. DBH	15.08	19.31	23.84	-	35.10	-	-		-	-	-	-	
#Trees	74	23	5	0	1	0	0	0	0	0	0	0	0
Pine													
Ave.%def	.35	.21	.74	0.0	.23	1.26	.07	0.0	-	-	-	-	
Ave. DBH	15.78	20.31	24.92	29.86	35.11	39.27	44.82	52.60	-	-	-	-	
#Trees	59	83	67	22	16	7	4	1	0	0	0	0	0
Aspen													
Ave.%def	1.61	8.77	2.72	9.30	8.18	22.78	1.28	-	-	-	-	-	
Ave. DBH	15.57	20.75	25.75	30.54	34.22	38.55	45.36	-	-	-	-	-	
#Trees	9	17	16	11	8	2	5	0	0	0	0	0	0
Balsam poplar													
Ave.%def	0.0	8.37	1.96	4.72	4.36	0.0	24.63	2.51	-	-	-	-	
Ave. DBH	14.23	21.73	25.04	30.38	35.88	39.10	43.97	47.80	-	-	-	-	
#Trees	3	7	7	9	4	3	3	1	0	0	0	0	0

Table IV.4iii. Defect percentages. Saw Class. Nonsuspect. VSR 4.

Species	DIAMETER CLASSES(cm) 0.0 to 17.8	17.8 to 22.8	22.8 to 27.8	27.8 to 32.8	32.8 to 37.8	37.8 to 42.8	42.8 to 47.8	47.8 to 52.8	52.8 to 57.8	57.8 to 62.8	62.8 to 67.8	67.8 to 72.8	72.8+
White spruce													
Ave.%def	0.0	.29	6.29	.30	1.46	9.36	9.15	0.0	-	-	13.26	-	
Ave. DBH	15.46	20.49	24.83	30.10	34.58	39.69	44.77	49.08	-	-	66.30		
#Trees	28	53	48	38	22	18	3	4	0	0	1	0	0
Black spruce													
Ave.%def	1.43	7.67	11.89	-	0.0	-	-		-	-	-	-	
Ave. DBH	14.85	19.58	25.06	-	35.10	-	-		-	-	-	-	
#Trees	60	21	7	0	1	0	0	0	0	0	0	0	0
Balsam fir													
Ave.%def	6.46	1.83	2.31	1.63	0.0	-	-		-	-	-	-	
Ave. DBH	16.04	20.44	24.28	29.72	36.60	-		-	-	-	-	-	
#Trees	10	19	5	6	1	0	0	0	0	0	0	0	0
Pine													
Ave.%def	2.21	2.61	2.38	3.39	0.0	0.0	0.0	-	-	-	-	-	
Ave. DBH	15.24	20.04	25.24	29.87	34.87	40.65	46.20	-	-	-	-	-	
#Trees	35	54	50	23	10	2	1	0	0	0	0	0	0
Aspen													
Ave.%def	3.11	10.59	4.64	0.0	4.58	-		-	-	-	-	-	
Ave. DBH	15.85	20.29	25.12	29.80	32.90	-	-	-	-	-	-	-	
#Trees	13	18	11	2	2	0	0	0	0	0	0	0	0
Balsam poplar													
Ave.%def	0.0	0.0	7.54	1.18	1.06	3.72	63.86	-	-	-	-	-	
Ave. DBH	15.00	20.20	25.23	29.14	34.27	40.10	45.20		-	-	-	-	
#Trees	2	2	3	5	3	2	1	0	0	0	0	0	0

Table IV.4iv. Defect percentages. Saw Class. Nonsuspect. VSR 8.

Species	DIAMETER CLASSES(cm) 0.0 to 17.8	17.8 to 22.8	22.8 to 27.8	27.8 to 32.8	32.8 to 37.8	37.8 to 42.8	42.8 to 47.8	47.8 to 52.8	52.8 to 57.8	57.8 to 62.8	62.8 to 67.8	67.8 to 72.8	72.8+
White spruce													
Ave.%def	3.23	3.58	1.13	2.38	1.47	5.30	11.17	0.0	.66	-	17.67	-	
Ave. DBH	13.91	20.24	25.45	30.33	35.06	39.29	44.72	50.16	54.86	-	64.15		
#Trees	72	70	55	45	34	29	12	5	8	0	2	0	0
Black spruce													
Ave.%def	0.0	4.21	9.01	0.0	-	-	-		-	-	-	-	
Ave. DBH	14.82	20.36	24.78	30.70	-	-	-		-	-	-	-	
#Trees	63	25	5	1	0	0	0	0	0	0	0	0	0
Pine													
Ave.%def	1.06	0.0	0.0	5.44	14.78	5.85		-	-	-	-	-	
Ave. DBH	15.29	20.01	25.14	30.51	34.04	39.95	-	-	-	-	-	-	
#Trees	49	43	18	18	7	4	0	0	0	0	0	0	0
Aspen													
Ave.%def	.23	4.91	1.05	3.64	.63	7.74	16.19	0.0	-	-	-	-	
Ave. DBH	14.84	20.15	25.05	29.78	34.89	39.42	43.00	47.90	-	-	-	-	
#Trees	89	66	44	18	7	9	1	1	0	0	0	0	0
Balsam poplar													
Ave.%def	15.49	7.73	7.72	11.13	11.87	0.0	8.89	-	-	-	-	-	
Ave. DBH	10.92	20.02	25.56	30.10	35.00	38.80	45.00		-	-	-	-	
#Trees	4	12	5	7	4	1	2	0	0	0	0	0	0

Table IV.5. Defect percentage. Pulp classes. Suspect.

VSR/Species group		SUSPECT CLASSES Scars & others	Broken top	Conk & Punk
VSR 3				
White spruce	Ave. %defect	2.16	6.02	0.0
	No. Trees	23	1	2
Black spruce	Ave. %defect	1.81	0.0	
	No. Trees	4	1	0
Pine	Ave. %defect	4.41	0.0	
	No. Trees	105	1	0
Aspen	Ave. %defect	2.46	-	
	No. Trees	4	0	0
VSR 2				
White spruce	Ave. %defect	1.22	0.0	
	No. Trees	12	2	0
Black spruce	Ave.%defect	4.25	0.0	
	No. Trees	23	1	0
Pine	Ave. %defect	.36	0.0	.97
	No. Trees	169	10	4
Aspen	Ave. %defect	5.62	-	17.56
	No. Trees	18	0	30
Balsam poplar	Ave. %defect	.72	.30	5.78
	No. Trees	18	2	5
VSR 4				
White spruce	Ave. %defect	10.19	0.0	37.55
	No. Trees	30	1	2
Black spruce	Ave. %defect	5.81	0.0	
	No. Trees	12	1	0
Balsam fir	Ave. %defect	4.16	-	
	No. Trees	13	0	0
Pine	Ave. %defect	2.15	0.0	
	No. Trees	102	8	0
Aspen	Ave. %defect	7.97	37.40	35.48
	No. Trees	21	6	77
Balsam poplar	Ave. %defect	9.24	40.44	
	No. Trees	4	3	0
VSR 8				
White spruce	Ave. %defect	10.02	5.76	
	No. Trees	34	51	0
Black spruce	Ave. %defect	5.63	-	0.0
	No. Trees	6	0	1
Pine	Ave. %defect	1.82	26.97	65.90
	No. Trees	58	3	2
Aspen	Ave. %defect	6.18	13.15	14.12
	No. Trees	28	2	87
Balsam poplar	Ave. %defect	2.74	15.37	12.49
	No. Trees	6	5	5

Table IV.6. Defect percentages. Saw class. Suspect.

VSR/Species group		SUSPECT CLASSES Scars & others	Broken top	Conk & Punk
VSR 3				
White spruce	Ave. %defect	13.30	0.0	
	No. Trees	11	1	0
Black spruce	Ave. %defect	7.02	0.0	
	No. Trees	2	1	0
Pine	Ave. %defect	9.61	-	
	No. Trees	74	0	0
Aspen	Ave. %defect	9.88	-	
	No. Trees	3	0	0
VSR 2				
White spruce	Ave. %defect	12.53	22.58	
	No. Trees	10	2	0
Black spruce	Ave.%defect	17.17	-	
	No. Trees	. 12	0	0
Pine	Ave. %defect	.96	0.0	15.26
	No. Trees	147	10	4
Aspen	Ave. %defect	14.25	-	36.92
	No. Trees	18	0	30
Balsam poplar	Ave. %defect	5.89	2.98	18.22
	No. Trees	16	2	4
VSR 4				
White spruce	Ave. %defect	16.37	0.0	64.61
	No. Trees	30	1	2
Black spruce	Ave. %defect	5.69	27.84.	0.0
	No. Trees	22	1	2
Balsam fir	Ave. %defect	10.11	-	
	No. Trees	13	0	0
Pine	Ave. %defect	5.23	0.0	
	No. Trees	92	8	0
Aspen	Ave. %defect	22.68	63.58	62.69
	No. Trees	15	5	74
Balsam poplar	Ave. %defect	14.64	84.15	
	No. Trees	4	3	0
VSR 8				
White spruce	Ave. %defect	16.00	7.29	
	No. Trees	31	51	0
Black spruce	Ave. %defect	21.30	-	
	No. Trees	5	0	0
Pine	Ave. %defect	7.38	64.43	68.89
	No. Trees	53	1	2
Aspen	Ave. %defect	19.88	13.24	27.27
	No. Trees	22	2	85
Balsam poplar	Ave. %defect	13.31	17.67	30.93
	No. Trees	14	5	5